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AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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THE RAFFETY BANDS IN COMETS

By N. T. BOBROVNIKOFF

ABSTRACT

Fourteen nuclear bands of unknown origin in the spectra of comets situated between λ 3987 and λ 4109 have been investigated in detail. Data compiled from determinations of the wave-lengths of these bands in twelve comets with slit-spectrographs have been used for this purpose. The wave-lengths correspond to those obtained in the laboratory by C. W. Raffety for the spectrum of the presumably *CH* molecule. The agreement is not complete. Neither the $^1\Pi-{}^1\Pi$ carbon system nor the cyanogen tail bands can be identified with the cometary bands.

The variation in brightness of the bands, depending on the heliocentric distance of the comet, shows that they form at least two systems. The intensity-curves fall between that of the *CH* band λ 4314 and the *CN* band λ 3883.

It is shown that the edges of eleven bands can be represented tolerably well by the formula $\nu = 24{,}335 + 71.0\,n - 0.1n^2$. Assuming the final state of the molecule that of the violet and red cyanogen systems the formula becomes

$$\nu = 24{,}328 + (2126.6v' - 13.85v'^2) - (2055.6v'' - 12.75v''^2)\ .$$

This formula gives a good representation of six more bands in the region where there are no other nuclear bands within several hundred angstroms. It is suggested that the *CN* molecule may be the carrier of these bands.

The remaining unidentified cometary bands are probably due to the *CH* molecule.

Celestial sources having carbon and cyanogen spectra have been compared with comets. *The bands in question appear to be typical for comets.*

The character of the cometary spectrum depends somewhat on the heliocentric distance r of the comet. Between the limits $r = 0.5$ and $r = 1.5$ astronomical units, where the majority of comets are observed, the Swan and the cyanogen bands are very prominent. They are very bright in comparison with the continuous spectrum of the comet and extend far from the nucleus, usually covering the whole coma. The next prominent system of cometary emission

bands is variously designated by CH_x, $C+H$, Raffety, hydrocarbon bands, etc. Its brightest members are situated in the region between λ 4000 and λ 4100. They are usually far less intense than the neighboring cyanogen band λ 3883. It is a nuclear band system, that is, its bands are very short, sometimes like stellar points on the objective-prism spectrograms. These bands were first observed in the laboratory by C. W. Raffety.[1] Miss A. E. Glancy[2] was the first to mention them as possibly occurring in the spectra of comets. In the laboratory Raffety obtained another system of bands situated in the same region and previously discovered by H. Deslandres and D'Azambuja.[3] Recent investigations[4] on the structure of the Deslandres-D'Azambuja bands seem to establish the fact that the carrier of these bands is the molecule C_2, which is also responsible for the Swan spectrum. This identification is of astrophysical interest as the Swan spectrum occurs in many celestial sources.

It has been suggested[5] that the unidentified cometary bands in the region between λ 4000 and λ 4100 may belong either to the Deslandres-D'Azambuja system or else to the so-called cyanogen tail system. However, the data on the spectra of comets are so fragmentary that the identification of the bands in question cannot be undertaken without a thorough revision of the existing observational material.

The difficulties involved in the measurement of cometary spectra are well known. The chief obstacle is the presence of the solar absorption lines in the continuous spectrum of the nucleus. A portion of the spectrum between two solar lines appears on the small dispersion spectrograms like an emission line or band. The wide slit ordinarily used in cometary spectroscopy introduces the blurring of details. In most cases the bands, which are presumably cometary Raffety bands, are described as lines. This confusion of terms, however, is of little importance in assuming them actually to be bands. Even strong Swan and cyanogen bands look on most come-

[1] *Philosophical Magazine*, **32**, 555, 1916.

[2] *Astrophysical Journal*, **49**, 196, 1919.

[3] *Comptes rendus*, **140**, 917, 1905.

[4] H. Kopfermann and H. Schweizer, *Zeitschrift für Physik*, **61**, 87, 1930; G. H. Dieke and W. Lochte-Holtgreven, *ibid.*, **62**, 767, 1930.

[5] R. C. Johnson, *Nature*, **125**, 89, 1930; *Monthly Notices of the Royal Astronomical Society*, **87**, 625, 1927.

tary spectrograms like lines. This is due partly to small dispersion, partly to peculiarities in the structure of cometary bands (restriction of rotational quantum transitions). Moreover, on good spectrograms of Halley's and Brooks's comets it is possible to see that most Raffety bands are degraded toward the violet, as the cyanogen and Swan bands.

The information on the cometary Raffety bands is not scarce but is distributed among various publications sometimes not readily accessible. The purpose of this paper is to systematize all the available astrophysical data bearing on the question. Particularly important would be the settling of the question of the identification of the cometary bands. It will be seen that wave-lengths of various bands observed in comets are far less discordant than might be anticipated, taking into account the difficulties of measurement. Consequently, they supply a definite answer as to the identity of the cometary bands with the Raffety laboratory system.

Fourteen comets whose spectra were obtained with slit spectrographs were used in this investigation. The list of comets is given herewith.

No.	Comet	Name	Authority	Reference
1....	1893 II	Rordame	W. W. Campbell	*Pub. A.S.P.*, **5**, 145, 1893
2....	1894 II	Gale	W. W. Campbell	*A.J.*, **14**, 111, 1894
3....	1899 I	Swift	W. H. Wright	*Ap.J.*, **10**, 173, 1899
4....	1903 IV	Borrelly	H. Deslandres	*C.R.*, **137**, 393, 1903
5....	1907 IV	Daniel	W. W. Campbell	*Lick Obs. Bull.*, **5**, 31, 1907
6....	1910 I	....	N. T. Bobrovnikoff	Unpublished
7....	1910 II	Halley	N. T. Bobrovnikoff	*Lick Obs. Pub.* (in print)
8....	1911 V	Brooks	W. H. Wright	*Lick Obs. Bull.*, **7**, 8, 1912
9....	1914 V	Delavan	Curtiss and McLaughlin	*Univ. of Mich. Pub.*, **3**, 264, 1923
10....	1914 I	Zlatinsky	V. M. Slipher	*Lowell Obs. Bull.*, **2**, 67, 1914
11....	1915 II	Mellish	V. M. Slipher	*Ibid.*, p. 151, 1916
12....	1919 III	Brorsen	V. M. Slipher	*Pub. A.S.P.*, **31**, 303, 1919
13....	1911 IV	Beliavsky	N. T. Bobrovnikoff	Unpublished
14....	1908 III	Morehouse	Campbell and Albrecht	*Lick Obs. Bull.*, **5**, 58, 1908

In comet Beliavsky the Raffety bands were exceedingly faint and could not be measured. In Morehouse's comet they were absent altogether.[1]

[1] F. Baldet (*Thèses: Sur la constitution des comètes*, p. 27, 1926) mentions an image of the head with traces of the tail on the objective-prism spectrograms between λ 4023 and λ 4068, of intensity 3(CN λ 3883 = 10). This may have been the Raffety bands.

The first question to be answered is whether all the bands in this region belong to the same system. If so, they should show the same variation in intensity with the heliocentric distance.

The photographic intensities of the brighter bands are given in Table I. The cyanogen head λ 3883 was assumed to be of intensity 10. In cases when the observer did not give the intensities they were calibrated from the verbal description and with the aid of reproductions. The most abundant data are those for Halley's comet. The intensities in this case were estimated by the writer during the measurement of the spectrograms. The comets are arranged according to their heliocentric distance r at the time of observation. The last twelve columns give the intensities of bands whose wave-lengths are indicated in the first line.

TABLE I

INTENSITIES OF COMETARY BANDS

Comet	r	3987 3993	4003	4014	4020	4042	4052	4067	4074	4086	4100	4109	4314
Beliavsky	0.33	....	....	....	0	0	1	0	0	....	....	....	3
1910 I	.47	1	1	1	1	1	2	1	1	1	1	1	4
Brorsen	.49	....	....	1	2	3	3	3	3	....	....	....	3
Brooks	.49	2	2	2	2	3	3	2	3	1	1	1	4
Daniel	.59	2	4	4	4	5	6	3	3	1	1	....	1
Halley	.59	1	1	2	2	4	3	2	2	....	....	....	0
Halley	.60	....	....	....	....	2	2	1	1	....	....	....	3
Halley	.63	1	1	1	1	2	3	1	1	1	....	....	....
Borrelly	.67	1	1	2	2	3	7	4	....	....	4	....	7
Zlatinsky	.68	1	2	2	2	3	4	3	3	1	1	2	6
Rordame	.69	1	....	3	5	5	5	....	5	....	5	....	8
Brooks	.72	1	1	3	3	3	4	2	2	1	1	1	6
Halley	.76	....	....	(2)	(2)	(2)	(5)	(1)	(3)	....	....	....	(7)
Halley	0.91	4	3	6	7	9	10	5	6	1	....	....	7
Halley	1.07	1	....	3	3	4	5	1	1	....	....	....	....
Halley	1.08	1	1	5	5	5	5	3	3	1	....	....	2
Gale	1.08	3	....	6	6	6	6	....	6	....	3	....	6
Delavan	1.20	....	....	....	....	1	5	....	2	....	....	....	....
Swift	1.31	3	....	6	6	6	8	....	5	....	3	....	6
Mellish	1.57	1	....	5	5	6	8	5	6	....	....	....	3

It is seen from the diagram (Fig. 1) that the brightest bands from λ 4014 to λ 4074 show the same variation of intensity in reference to the cyanogen band λ 3883. They all increase in intensity with the increasing heliocentric distance, giving a flat maximum in the neighborhood of $r=1.2$. The frequent variations in brightness may be

due to the change in the intensity either of the Raffety bands or else of the cyanogen band, λ 3883. The cyanogen bands themselves[1] rapidly increase in intensity between $r=0.3$ and $r=0.5$, but remain approximately of the same intensity between $r=0.5$ and $r=1.5$, so that the intensity of the brighter Raffety bands in comets shows a somewhat greater dependence on the heliocentric distance as compared with the cyanogen bands. This is in accordance with the results of Frank S. Hogg, who studied cyanogen band λ 3883 and Raffety λ 4109. This may mean that the carrier of the Raffety bands is less stable than the molecule of CN.

For the fainter bands the data are more fragmentary. It appears that on both sides of the bright group $\lambda\lambda$ 4014–4074 the dependence on the heliocentric distance as compared with the cyanogen band λ 3883 is less pronounced.

Under the laboratory conditions the Raffety bands seem to be associated[2] with the hydrocarbon band at λ 4314. This band falls in the region of the Fraunhofer line G, and its intensity is difficult to estimate. From the available data it appears that this hydrocarbon band in comets shows approximately the same variation of intensity as the brighter Raffety bands (Table I and Fig. 1).

The association of the Raffety bands with the CH band in comets is probably not close. Comet Delavan did not show the CH band although the Raffety bands were strong. Still more striking contrast between the behavior of these two sytems is afforded by comets Zlatinsky and Mellish. In the former the CH band was very strong and the Raffety system weak as compared with the CN λ 3883. The latter had just the opposite.

The wave-lengths in angstroms are given in Table II. The weights for the comets were assigned in accordance with the number of spectrograms taken, quality of spectrograms, etc. For the wave-lengths of Raffety bands the mean of Raffety's three measurements was taken. The wave-lengths of cometary radiations obtained by Baldet from a large number of objective-prism spectrograms are also given. They are in good agreement with the mean from the slit spectrograms. The wave-lengths in parentheses were not used in forming

[1] F. S. Hogg, *Journal of the Royal Astronomical Society of Canada*, **23**, 55, 1929.

[2] C. W. Raffety, *loc. cit.;* F. Baldet, *op. cit.*, p. 103.

the mean. They are clearly blends of the band with the following one. In most cases the authors suspected a duplicity of the bands

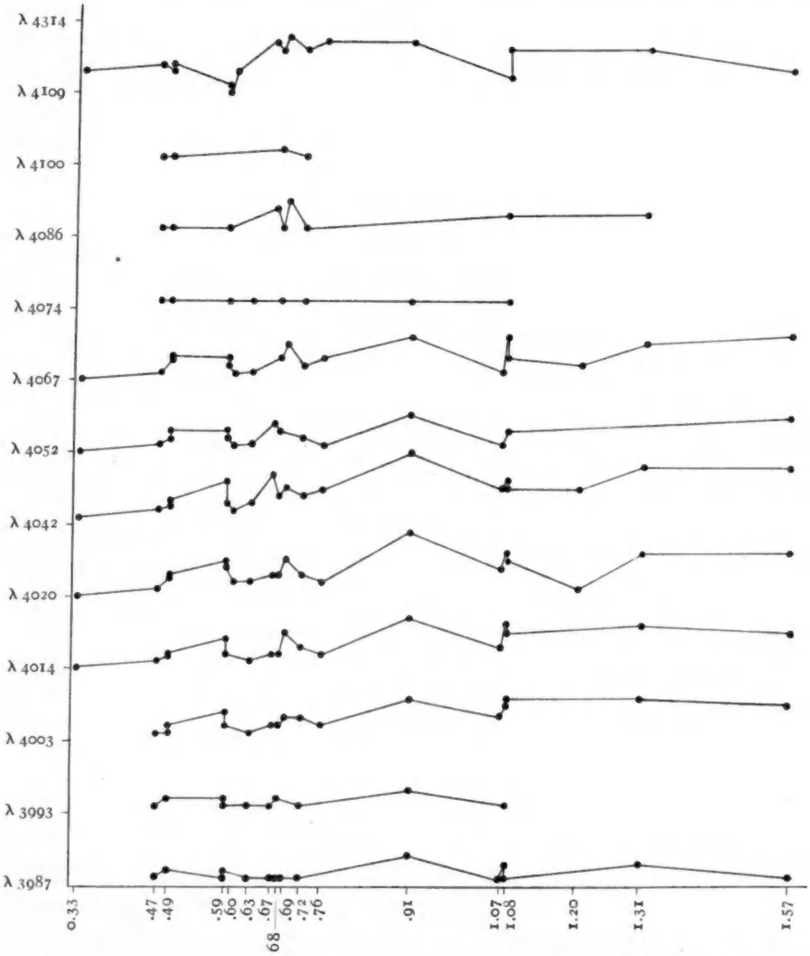

FIG. 1.—Photographic intensities of Raffety bands in reference to *CN* λ 3883. Each division of the ordinate corresponds to intensity 10 (=assumed intensity of λ 3883). Abscissa represents the heliocentric distance.

in question. The wave-lengths were used as they were given by the authors, although in a few cases (with low weight) it was not clear from the text whether the correction for the Doppler effect had been applied.

The last column of Table II contains the wave-lengths of the cometary band at λ 4314.0. This is undoubtedly the hydrocarbon band λ 4300, which gives a strong head at λ 4314.3. In the derivation of the mean the wave-length λ 4313.1 as observed in comet Beliavsky (weight 1) was included.

In addition to the fifteen bands listed in Table II a few more faint bands were observed between λ 3988 and λ 3883. Thus bands $\lambda\lambda$ 3975, 3963, and 3952 were observed in comets Brooks and Halley. Baldet's list includes also the following nuclear lines which may be connected with the Raffety system: $\lambda\lambda$ 3910.9, 3968.4, 4124.5, 4230, 4238, 4255.8, 4264.2, 4291.7, 4301.4, 4304.2, 4329, 4335, 4350, 4412, 4430, 4440, 4477, 4724.2, 4840.4, 4928.5, 6300.

The agreement between the cometary radiations and Raffety bands as observed in the laboratory is satisfactory, taking into account the difficulty of measurement. Too small wave-lengths in comets for the bands λ 4039.3 and λ 4052.1 may be explained by blends with the Raffety bands λ 4037.3 and λ 4047.5. The outstanding difficulty is presented by one of the brightest bands, λ 4042.4, which is 1.1 A too small. The measurements are numerous and in good agreement, so that the discrepancy seems to be real. It is also impossible to explain by accidental departure the large wave-length of λ 4099.6 as compared with the laboratory λ 4095.0. In this case the objective-prism wave-length is exactly the same as from the slit spectrograms.

It is difficult to account for the absence of the Raffety band λ 4025.2 from the cometary spectrum.[1] Its wave-length in the laboratory is given by Baldet as λ 4026.5, and its intensity in the Mecker burner approaches that of the brightest cometary band of this system, λ 4052. The objective-prism spectrograms also have no trace of a band near λ 4025. The nearest bands on both sides are λ 4020.0 and λ 4031.5. The latter is evidently the Raffety band λ 4031.5.

There are several more bands to the violet of λ 4031 which have no counterpart in the Raffety laboratory system. This may be explained by the faintness of the Raffety bands in the Mecker burner. They were observed by Raffety as merely traces while the *CH* band

[1] Only one comet (Borrelly) had a band at λ 4027.1.

TABLE II

Wave-Length of Cometary Bands

Comet	w	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ	λ
1	1	3988	......	......	4011.2	4019.2	......	......	4043.1	4052.3	(4072.7)	......	......	4097.9	......	4313.0
2	1	3987	......	......	(4015.7)	......	......	......	4040.9	4050.5	(4070.7)	......	......	4097.4	......	4312.6
3	1	3987	......	......	4014	4019.0	......	......	4041.5	4052.5	......	4074	......	4100.5	......	4313
4	1	3985.2	(3998.1)	(4008.1)	......	(4027.1)	......	......	4043.2	4052.2	4063.3	......	......	4101.4	......	4314.3
5	2	3990	......	4003	4014	4020.0	......	4039.0	4042.8	4052.9	4068.8	4074.0	......	......	......	4313.8
6	1	......	(3997.7)	......	......	4019.4	......	......	4042.9	4053.1	......	......	(4093.5)	......	4108.2	4312.5
7	4	3983.0	3993.0	4003.1	4014.9	4020.6	4030.9	4038.9	4042.5	4052.5	4068.8	4074.8	4085.2	......	4109.4	4314.7
8	1	3988	3992.6	4001.6	4013.7	4019.6	4033.1	4040.0	4043.0	4051.5	4068.9	4074.6	4086	4098.8	4109	4312.2
9	2	......	......	......	......	......	......	4040.0	4044.2	4052.7	......	4074.9	......	......	......	......
10	2	3991.9	......	4003	4014.4	4020.2	4032	......	4042.4	4051.5	4066.5	4073.7	4087	4100.5	4109	4313.3
11	3	......	3994	......	(4017.5)	......	......	......	4041.1	4051.7	4065.4	4073.6	......	......	......	4316.4
12	1	......	......	......	4016.1	4020.3	......	......	4042.1	4050.6	4066.6	4073.8	......	......	......	4313.5
Weighted Mean		3987.0	3993.3	4002.9	4014.3	4020.0	4031.5	4039.3	4042.4	4052.1	4067.2	4074.2	4085.8	4099.6	4109.1	4314.0
P.e. of mean		±0.8	±0.3	±0.2	±0.3	±0.1	±0.4	±0.3	±0.2	±0.1	±0.5	±0.1	±0.2	±0.4	±0.2	±0.3
Raffety lab.		......	......	......	......	......	4031.5	{4039.9 4037.3}	4043.5	{4052.9 4047.5}	4065.6	4074.4	4084.5	4095.0	4107.4	4314.3
Baldet comets		3988.4	3993.1	4002.0	4014.5	4020.1	4032.6	4039.6	4043.0	4051.6	4067.7	4074.0	4085.1	4099.6	4109.3	4313.8

at λ 4314 was very bright. It was at least ten times as bright as the brightest Raffety band at λ 4052. In comets, on the other hand, the Raffety bands are very strong, sometimes even stronger than the *CH* band (Table I). This, of course, implies a different way of excitation of the cometary bands if indeed they belong to the same molecule *CH*.

The new carbon system, or Deslandres-D'Azambuja bands, were produced by the discoverers in a condensed discharge through *CO* or CO_2. Raffety observed them in the spark through alcohol. Dieke and Lochte-Holtgreven produced them by condensed discharge through acetylene. Kopfermann and Schweizer obtained these bands in a carbon arc. In all cases they were found to be associated with the ordinary Swan bands. The new system is due to the electronic transition $^1\Pi - ^1\Pi$ of the carbon molecule, while the Swan bands belong to the $^3\Pi - ^3\Pi$ transition. According to Kopfermann and Schweizer, the lower electronic level of the $^1\Pi - ^1\Pi$ system is only one volt above the lower level of the $^3\Pi - ^3\Pi$ system, so that their upper levels should be approximately two volts apart.[1] This fact accounts for the occurrence of the new system together with the Swan bands, and also for the greater brightness of the Swan bands.

We may, therefore, look for the new carbon system in comets. The bands, as given by Dieke and Lochte-Holtgreven, have the usual "parabolic" distribution of brightness. The brightest (0, 0) head is at λ 3852.1; that is, it nearly coincides with the (3, 3) head (λ 3854.7) of the violet cyanogen system. The cyanogen bands in comets decrease in intensity very rapidly. Only two first members of the sequence $v''-v'=0$ are usually observed, so that if the (0, 0) band of the new carbon system were present it would give an easily detectable head. However, none of the fourteen comets considered in this paper gave any indication of its existence. On the photometer tracings of the spectrum of Halley's comet (April 24, 1910), the (2, 2) and (3, 3) cyanogen bands were represented by very slight elevations corresponding to intensities of 1–2 if the intensity of the (0, 0) cyanogen band is taken as 100. The intensity of the brighter cometary Raffety bands would be 20–30 on the same scale. It is

[1] We have for the Swan bands $\nu_0 = 19374$ cm^{-1}, and for the new system $\nu_0 = 25969$ cm^{-1}, the difference being 6595 cm^{-1}, or 0.8 volts.

clear that the (0, 0) band of the $^1\Pi-^1\Pi$ carbon system contributes very little or nothing to the brightness of the (3, 3) cyanogen band. But this, perhaps, is not a fair test, as the ordinary glass transmits little light to the shorter wave-lengths of the cyanogen band λ 3883. There is also no doubt that in the cometary Swan system the intensities of the individual bands are shifted toward the violet, that is, toward the higher vibrational transitions, as compared with the laboratory, so that the (0, 0) band of the new carbon system may well be too weak for detection in comets.

The next brightest band in the $^1\Pi-^1\Pi$ carbon system is (1, 0) λ 4102.3. It has not been measured in comets as an individual band. The proximity of the solar H_δ λ 4101.9 would tend to diminish considerably the brightness of the carbon emission band. On the other hand, the wave-length of Raffety band λ 4095.0 (measured by Baldet at the same wave-length) is impossible to reconcile with the wave-length λ 4099.6 observed in comets. It would seem that the cometary band λ 4099.6 is a blend of the Raffety band λ 4095.0 and carbon λ 4102.3. This cometary band is very faint as compared with the rest of the bands in this region, so that if the carbon band is present it must be very weak.

The next band of the new carbon system (2, 1) λ 4062.2 is too far from the cometary λ 4067.2 to have any connection with it. The Raffety band λ 4065.6 (measured by Baldet at λ 4067.1) is much nearer.

The faint band (3, 2) λ 4026.9 of the new system cannot be identified with any of the cometary bands. In view of this it is improbable that the higher transitions of the +1 sequence would occur in comets. As a trial, applying Kopfermann and Schweizer's formula for the edges of the bands,

$$\nu = 25{,}952 + (1789.14v' - 23.0v'^2 - 4.16v'^3) - (1594.8v'' - 12.7v''^2)\,,$$

we obtain the following wave-lengths: (5, 4) λ 4028; (6, 5) λ 4049; (7, 6) λ 4094; (8, 7) λ 4170. The nearest unidentified cometary radiations are at λλ 4031, 4052, 4100, and 4185; that is, there is no satisfactory correspondence.

It appears, therefore, that the new carbon system if present at all in comets must be extremely weak in comparison with the Raffety

and other bands in comets. This is surprising in view of the great intensity of the Swan bands in comets and small difference in the electronic level of both systems.

R. C. Johnson suggested the possible identification of the cometary bands with the cyanogen "tail bands." These are situated on both sides of the (0, 0) sequence of cyanogen and are due[1] to higher vibrational transitions of the *CN* molecule. They begin in sequence 0 at (10, 10) while the main bands end at transition (3, 3). The brightest band (10, 10) is at λ 3894.1 (null line), and is one-fourth of the intensity of the main cyanogen band λ 3883 (in active nitrogen). It should therefore be readily measurable in the cometary spectra. It appears to be entirely absent in comets. Next in brightness bands (11, 11) λ 3920.8 (null line); (12, 12) λ 3944.6 (head); (13, 13) λ 3984.7 (head); (14, 14) λ 4029.3 (head); and (15, 15) λ 4078.7 (head) cannot be satisfactorily ascribed to any radiations in comets, although some of them fall within several angstroms of the observed bands. The absence of the brightest band from the spectra of comets seems to be proof of the real absence of the cyanogen tail bands in comets.

The presence of the cometary bands at λλ 3987, 3993, 4003, 4014, 4020, is disconcerting in view of the fact that the Raffety band λ 4025 is absent, being presumably too faint in comets. The members of this system farther to the violet should be still fainter. Hogg identified the above-mentioned bands with the secondary maxima in the continuous solar spectrum at λλ 3988, 3993, 4003, 4013, 4019. It is difficult to accept this identification. All these bands show a similar dependence on the heliocentric distance as the brighter Raffety bands (Fig. 1). If they were features of the reflected solar light, such dependence would be incomprehensible. We should expect just the opposite to what is the case, namely, a rapid decrease in brightness of these pseudo-bands with the increasing heliocentric distance. Furthermore, the objective-prism spectrograms give practically the same wave-lengths for these bands which appear as well-defined points on the nuclear line, sometimes[2] as bright as the Raffety band

[1] F. A. Jenkins, *Physical Review*, **31**, 539, 1928.

[2] See, for instance, the reproduction of the spectrum of Halley's comet in *Astrophysical Journal*, **66**, Plate V, 1927.

λ 4052. Moreover, their frequencies show numerical relationships with the rest of the bands. There is little doubt that they are true cometary radiations.

By examining the differences in ν_{vac} of the bands it was found that at least eleven bands gave an approximately constant difference $\Delta\nu = 71$, so that their edges could be represented tolerably well by the Deslandres formula

$$\nu = a + bn + cn^2 ,$$

with $a = 24{,}335$, $b = 71$, $c = -0.1$, n varying from 0 to 10. This cannot be a Deslandres n' progression as in this case we have to assume $\omega_0' = 71$. In this case, however, we would have an impossibly large moment of inertia for the molecule. It is evident that $\Delta\nu = 71$ should be equal to $\omega_0' - \omega_0''$ and that $\omega_0' x' - \omega_0'' x''$ should be as small as 0.1 cm^{-1}. Among the familiar molecules abundant in comets only cyanogen and CH meet the requirements. We have[1] the two known cyanogen systems:

$$\text{Violet } \nu = 25797.8 + (2143.9v' - 20.25v'^2) - (2055.6v'' - 13.75v''^2) ,$$

$$\text{Red } \nu = \left.\begin{matrix} 14{,}430 \\ 14{,}374 \end{matrix}\right\} + (1728.5v' - 13.5v'^2) - (2055.6v'' - 13.75v''^2) .$$

Both systems have the same final level $^2\Sigma$, which is probably the normal state of the molecule. In the violet system $\omega_0' - \omega_0'' = 88$ cm^{-1} and $\omega_0' x' - \omega_0'' x'' = 6.5$ cm^{-1}. In the red sytem the same differences are 227 cm^{-1} and -0.25 cm^{-1}. Both systems are present in great intensity in the spectra of comets. As the cometary spectrum is probably of a fluorescent origin we should expect the lower level to be the normal state of the molecule. Therefore, the only permissible arrangement is that of the electronic level and of the upper level. After several trials the following formula was adopted:

$$\nu = 24{,}335 + (2126.6v' - 13.85v'^2) - (2055.6v'' - 13.75v''^2) ,$$

which represents the observations as shown in Table III.

It is clear that the cometary bands can be better represented by $\nu_0 = 24{,}328$, so that there is a systematic difference in the frequency

[1] All data relating to the molecular constants were taken from R. T.Birge, *International Critical Tables*, **5**, 409, 1929.

between the laboratory and cometary bands amounting to 7 cm^{-1} (1.1 A). This is probably due to the wide slit with which the cometary spectrograms are usually taken.

The agreement between the calculated and observed values may be considered satisfactory as both laboratory and cometary wavelengths are not precise.[1] The cometary band λ 4099.6 probably does not belong to this sequence.

If Table III represents the zero sequence of the hypothetical new system, the test of the hypothesis would be the appearance of other

TABLE III

Computed and Observed Frequencies of the Raffety Bands

$v'=v''$	λ Lab.	λ Comets	ν Lab.	ν Comets	ν Calc.	Δν	
						Lab. − Calc.	Comets − Calc.
0.......	4107.4	4109.1	24,340	24,329	24,340	0	−11
1.......	4095.0	(4099.6)	24,413	(24,386)	24,411	+ 2	(−25)
2.......	4085.5	4085.8	24,476	24,467	24,482	− 6	−15
3.......	4074.4	4074.2	24,537	24,538	24,552	−15	−14
4.......	4059.7	....	24,626	....	24,622	+ 4	....
5.......	4047.5	....	24,700	....	24,692	+ 8	....
6.......	4037.3	4039.3	24,762	24,750	24,762	0	−12
7.......	4025.2	....	24,837	....	24,832	+ 5	....
8.......	....	4014.3	....	24,904	24,902	....	+ 2
9.......	....	4002.9	....	24,975	24,971	....	+ 4
10.......	....	3993.3	....	25,035	25,040	....	− 5

sequences in the nuclear spectrum of comets. Table IV shows the results (assuming $\nu_0 = 24{,}328$ cm^{-1}).

In Table IV the data for the comets were taken from Baldet's work. The correspondence is not very close, yet taking into account the difficulty of measurement on the objective-prism spectrograms it can hardly be called accidental. Especially convincing is the fact that in the range of 2821 cm^{-1} (= 274 A) there are only four nuclear bands and all of them correspond to the +1 sequence within several angstroms. The same applies to the (2, 0) band. There is only one nuclear band within the range of 4787 cm^{-1}, and this falls within 12 cm^{-1} of the (2, 0) band. The bands (3, 0) and (4, 0) fall in the region

[1] For the first band Raffety's individual measurements are λ 4106.7 and λ 4108. Baldet gives for the same band λ 4110. It should also be remembered that the measurements refer to the heads, whereas the constants in the formulae refer to the origins.

of the Swan bands and cannot be easily observed. The band (0, 1) is too far to the violet to be observed in comets.

It appears, therefore, that the majority of the Raffety bands may belong to a cyanogen system. This not only explains the appearance in comets of the bands λλ 4014.3, 4002.9, 3993.3 due to transitions with the higher quantum numbers, but also accounts for the several bands in the less refrangible part of the spectrum. We know that the red cyanogen system has two very close electronic levels $^2\pi$; This argument is not applicable to the new system as the constants in the term with v' differ considerably from those in the violet system. The distribution of intensity among the vibrational

TABLE IV

FURTHER SEQUENCES OF THE RAFFETY BANDS

v''	v'	Calc.	Comets	$\Delta\nu_{O.-C.}$	Comets
0	1	26,441	....	....	....
1	0	22,286	22,330	....	Probably blend, λ 4477
2	1	22,384			
3	2	22,483	22,516	+33	λ 4440
4	3	22,581	22,567	−14	λ 4430
5	4	22,680	22,659	−21	λ 4412
2	0	20,272	20,284	+12	λ 4928.5
3	0	18,285	18,276	− 9	Swan (5,4)
4	0	16,326	16,330	+ 4	Swan (3,1)

quantum numbers in the new system also differs from that in the violet cyanogen system. Instead of the usual parabola in the v', v'' matrix we have the $v''-v'=0$ sequence of the maximum brightness. This of course may mean a very narrow parabola. However, as the lower vibrational level was assumed to be that of the *CN* molecule, this analysis perhaps should be regarded as a suggestion rather than a definite identification.

The remaining unidentified cometary bands in the region between λ 3987 and λ 4126 are as shown in Table V.

The last wave-length was taken from Baldet's list. The differences do not reveal much regularity except for the occurrence $\Delta\nu = 50$ or 51. These bands cannot be a progression, so that $\Delta\nu$ should approximately represent the difference $\omega_0'-\omega_0''$. These bands, among which are the brightest cometary bands of the whole group, λλ 4052.1 and 4042.4, may be connected with the *CH* system ($\omega_0'-\omega_0''=54$ and 36). In that case the laboratory production of the Raffety bands

along with the CH bands λ 4314 would be explained. Lack of data for the CH bands prevents a more detailed analysis.

The existence of two systems in the Raffety bands, one associated with CN and the other with CH, would explain the variation in their intensity which follows a middle path between the CN and CH systems. Further laboratory data are needed for a complete identification. For the present we must be content with the establishment of some relationships between the cometary and laboratory bands.

The Raffety bands, taken as a whole, are brighter at larger heliocentric distances and are usually present in comets at $r=0.5$. They

TABLE V

λ	ν	$\Delta\nu$
3987.0	25,074	
		205
4020.0	24,869	
		71
4031.5	24,798	
		48
4039.3	24,750	
		19
4042.4	24,731	
		59
4052.1	24,672	
		286
4099.6	24,386	
		151
4125.8	24,235	

are ordinarily considerably fainter than the cyanogen band λ 3883: A striking exception to this rule was the periodic comet Pons-Winnecke in 1927 ($r=1.0$). The Raffety bands were considerably brighter than the cyanogen λ 3883. On the other hand, comet Morehouse ($r=0.94$) did not show any traces of the Raffety bands, although both cyanogen and Swan bands were intense. It seems, therefore, that individual characteristics of the comet come into play. The intensity of the Raffety system in comets follows in general the intensity of the CH band λ 4314. The absence of the Raffety bands in Morehouse's comet can be correlated with the absence of the CH band. On the other hand, the extremely bright Raffety bands in Pons-Winnecke's comet were not accompanied by bright CH bands. Under the laboratory conditions the Raffety bands are associated with the CH bands, but this is not the proof of their origin.

It is of interest to compare other celestial sources with comets. The flash spectrum contains the cyanogen, Swan, and CH spectrum.[1]

[1] S. A. Mitchell, *Astrophysical Journal*, 71, 1, 1930.

The cyanogen λ 3883 is of intensity 10 in the flash and ascends to 750 km. If the Raffety bands approached in intensity the cyanogen bands in the chromosphere, as they do in comets, they could not be missed. There are numerous faint metallic lines in this region and the identification is impossible. The brightest Raffety band at λ 4051.6 is probably absent. The two neighboring lines have wave-lengths 4050.9 and 4052.1 of intensity 2 and 3. The same is true of the Raffety band λ 4043.5, which falls between the metallic lines 4042.9 and 4044.0 of intensity 8 and 4. It is probable that the Raffety bands do not occur in the flash spectrum. The *CH* bands in the flash spectrum are faint. The laboratory wave-lengths of the Raffety bands are not precise enough to allow a comparison with the solar spectrum.[1] All the bands as given by Raffety coincide almost exactly with the unidentified lines in the solar spectrum. However, in view of the number of the faint, unidentified lines in the solar spectrum this coincidence is probably accidental, the more so as they are not intensified in the spots.

Of other cosmic sources the stars of classes R and N should be examined. The intermediate classes from R3 to R5 have very strong cyanogen, Swan, and hydrocarbon bands.[2] The Raffety bands, or any bands in the region between λ 4000 and λ 4100, are completely absent.

The lack of precision both of the laboratory and of cometary wave-lengths does not allow certain identification of the cometary bands with the Raffety system. The identification seems, nevertheless, highly probable. It appears that the Raffety bands are more characteristic of comets than either cyanogen or Swan bands, as of all celestial sources only comets give well-defined bands apparently coinciding with the Raffety system. It seemed worth while to draw the attention of experimental physicists to the desirability of further work on this interesting system.

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[1] Revision of Rowland's "Preliminary Table." *Papers of the Mount Wilson Observatory*, **3**, 1928, Carnegie Institution of Washington.

[2] C. D. Shane, *Lick Observatory Bulletin*, No. 396, 1928.

PHOTOMETRIC AND SPECTROGRAPHIC ORBITS OF TT AURIGAE[1]

BY ALFRED H. JOY AND BANCROFT W. SITTERLY

ABSTRACT

Photometric observations of the eclipsing star TT Aurigae were made with the *polarizing photometer* at Princeton in 1910–1911 and 1915. The variable was compared with B.D.+39°1191. The *spectrographic* observations were made at Mount Wilson, 1917–1930.

The photometric observations and period.—Table I gives the 693 photometric observations of the difference in magnitude between the variable and the comparison star, together with the weights assigned. The period used was determined from the observed minima. The elements are

$$\text{Min.} = \text{J.D. } 2419065.9041 \text{ H.G.M.T.} + 1^{\text{d}}332732E .$$

The photometric orbit.—The *light-curve* is of the *β Lyrae type. Ellipsoidal stars and a reflection effect* are indicated, but the evidence is against darkening at the limb. Because the duration of secondary eclipse is less than that of primary eclipse, the circular uniform elements can be slightly improved by introducing an orbital eccentricity of 0.09 with perihelion at secondary minimum. The primary eclipse is annular: $i = 88^\circ.4$; $k = 0.90$; $r_1 = 0.36$; $r_2 = 0.32$; $b_1 = 0.31$; $b_2 = 0.27$; $\sqrt{z}/\sin^2 i = 0.54$; $L_1 = 0.66$; $L_2 = 0.34$; $J_1/J_2 = 1.56$; $2s = 0.05$.

The spectrographic observations and orbit.—The data for 32 spectrograms are listed in Table IV. The type of the bright star is B3 with poor lines. The spectrum of the fainter star seems to be similar. The lines of interstellar calcium are strong and give a mean velocity of +4.3 km/sec. The elements are: $e = 0.0$; $\gamma = +10.2$ km/sec.; $K_1 = 196.8$ km/sec.; $K_2 = 246.1$ km/sec.; $a_1 \sin i = 3{,}600{,}000$ km; $a_2 \sin i = 4{,}500{,}000$ km; $m_1 \sin^3 i = 6.7 \odot$; $m_2 \sin^3 i = 5.3 \odot$.

Absolute dimensions.—Photometric and spectrographic results were combined to find the absolute dimensions: $a_1 + a_2 = 8{,}100{,}000$ km; $r_1 = 4.5 \odot$; $r_2 = 4.0 \odot$; $b_1 = 3.7 \odot$; $b_2 = 3.3 \odot$; $m_1 = 6.7 \odot$; $m_2 = 5.3 \odot$; $\rho_1 = 0.11 \odot$; $\rho_2 = 0.12 \odot$; $M_1 = -1.2$ mag.; $M_2 = -0.9$ mag.; $\pi = 0.001$.

TT Aurigae ($5^{\text{h}}2^{\text{m}}.8$, $+39^\circ 27'$, 1900; 8.0–9.4 mag.) is an eclipsing star of early type. Miss Leavitt in 1907 found it to be variable. The variation was confirmed by S. Enebo[2] and by W. Münch,[3] who suspected that the curve outside eclipse was rounded like that of β Lyrae; but they failed to note the difference in depth of alternate minima which necessitated doubling the period. In 1910–1911 Joy made the observations presented in this paper. At the time these revealed the character of the light-curve, but the results have not heretofore been published.

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 419.

[2] *Astronomische Nachrichten*, **180**, 63, 1909.

[3] *Ibid.*, **182**, 125, 1909.

J. Balanowsky[1] made a series of 175 observations with the Zöllner photometer at Pulkowa in 1911–1913 from which he deduced orbital elements and the relative dimensions of the stars. Extensive photographic observations have been carried out by C. Martin and H. C. Plummer (1914–1916)[2] and by F. C. Jordan (1914–1916 and 1922).[3] A number of observations have been reported by A. A. Nijland (1917–1920),[4] but the individual estimates have not been published.

I. THE PHOTOMETRIC OBSERVATIONS

The photometric observations (Table I) were obtained at Princeton with the sliding-prism photometer attached to the 23-inch refractor. The instrument and methods employed are the same as those used by R. S. Dugan in his well-known work on eclipsing stars. Six hundred and ninety-three sets of sixteen readings each were made, TT Aurigae being compared with the neighboring star B.D. $+39^\circ 1191$ by bringing the stars side by side and reducing them to apparent equality by rotating the nicol prism. Since the comparison star (8.02 mag.)[5] is somewhat brighter than the variable at its brightest, all the magnitude differences have the same sign. According to the *Draper Catalogue* the comparison star, like the variable, is of spectral type B5. Their colors seem to be very closely alike.

The phases given in Table I were computed from the elements

$$\text{Min.} = \text{J.D. } 2419065.9041 \text{ H.G.M.T.} + 1^{\mathrm{d}}\!.332732E\ ,$$

which were determined from a least-squares solution based on the times of twelve minima indicated by these observations.

II. THE PHOTOMETRIC ORBIT

The final photometric orbit and elements have been computed by Sitterly, although some preliminary solutions had previously been made by H. N. Russell and Joy. The observations given in Table I

[1] *Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowa*, **5**, 123, 1913.

[2] *Monthly Notices of the Royal Astronomical Society*, **76**, 395, 1916.

[3] *Publications of the Allegheny Observatory*, **7**, 177, 1929.

[4] *Astronomische Nachrichten*, **211**, 358, 1920.

[5] *Annals of the Harvard College Observatory*, **63**, 156, 1913.

TABLE I

Photometric Observations of TT Aurigae

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
J.D. 241+				8974.7819	0.8363	0.46	3
8961.7021	1.0838	0.33	2	8974.7937	.8482	.42	3
8961.7111	1.0928	.35	2	8974.8049	.8593	.33	3
8961.7306	1.1123	.48	2	8974.8514	.9058	.38	3
8961.7465	1.1282	.48	3	8974.8597	.9141	.37	4
8961.7708	1.1525	.42	3	8974.8701	.9245	.27	4
8961.7833	1.1650	.43	3	8974.8806	.9350	.35	3
8961.8000	1.1817	.51	3	8974.8910	.9454	.34	3
8961.8125	1.1942	.53	3	8974.9049	.9593	.26	1
8962.7188	0.7678	.55	2	8975.6604	.3821	.35	4
8962.7299	.7789	.56	3	8975.6674	.3891	.35	5
8962.7424	.7914	.50	2	8975.6750	.3967	.36	5
8962.7528	.8018	.36	3	8975.6819	.4036	.36	5
8962.7667	.8157	.43	3	8975.6896	.4113	.29	5
8962.7778	.8268	.39	3	8975.6965	.4182	.32	5
8962.7889	.8379	.44	3	8975.7257	.4474	.38	5
8962.8021	.8511	.46	3	8975.7347	.4564	.35	5
8962.8118	.8608	0.47	3	8975.7424	.4641	.42	5
8968.6208	.0061	1.41	3	8975.7500	.4717	.42	5
8968.6333	.0186	1.48	2	8975.7611	.4828	.39	5
8968.6458	.0311	1.15	3	8975.7681	.4898	.41	5
8968.6563	.0416	0.94	3	8975.8056	.5273	.51	5
8968.6674	.0527	1.06	3	8975.8125	.5342	.41	5
8968.6889	.0742	0.87	2	8975.8389	.5606	.39	5
8968.6979	.0832	.83	3	8975.8465	.5682	.48	5
8968.7090	.0943	.69	3	8975.8535	.5752	.56	5
8970.7458	.7984	.69	0	8975.8611	.5828	.49	5
8970.7639	.8165	.56	2	8975.8806	.6023	.54	5
8970.7972	.8498	.49	2	8975.8882	.6099	.57	5
8970.8444	.8970	.39	3	8975.8965	.6182	.59	5
8970.8549	.9075	.35	3	8975.9090	.6307	.76	5
8970.8729	.9255	.46	2	8975.9160	.6377	.69	4
8970.8910	.9436	.40	3	8975.9278	.6495	.71	4
8970.9049	.9575	.55	3	8975.9347	.6564	.70	4
8970.9264	.9790	.37	3	8975.9417	.6634	.82	3
8970.9347	.9873	.44	3	8976.6729	.0619	.86	2
8970.9458	.9984	0.37	2	8976.6785	.0675	.86	4
8974.6264	.6808	1.04	2	8976.6861	.0751	.75	5
8974.6340	.6884	0.92	3	8976.6917	.0807	.67	5
8974.6424	.6968	.88	3	8976.6972	.0862	.63	5
8974.6493	.7037	.79	3	8976.7028	.0918	.75	5
8974.6576	.7120	.70	3	8976.7215	.1105	.55	5
8974.6681	.7225	.64	3	8976.7285	.1175	.56	5
8974.6958	.7502	.56	3	8976.7347	.1237	.52	5
8974.7028	.7572	.49	3	8976.7417	.1307	.57	5
8974.7104	.7648	.39	3	8976.7479	.1369	.59	5
8974.7167	.7711	.51	3	8976.7535	.1425	.43	4
8974.7250	.7794	.42	2	8976.7819	.1709	.31	4
8974.7326	.7870	.47	3	8976.7882	.1772	.48	5
8974.7590	.8134	.44	3	8976.7944	.1834	.44	5
8974.7667	.8211	.51	3	8976.8139	.2029	.45	5
8974.7736	0.8280	0.44	3	8976.8243	0.2133	0.41	5

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
8976.8333	0.2223	0.32	5	8982.8354	0.8934	0.42	5
8976.8514	.2404	.36	5	8982.8542	.9122	.31	5
8976.8611	.2501	.43	4	8982.8646	.9226	.44	5
8976.8729	.2619	.32	4	8982.8736	.9316	.28	4
8976.8826	.2716	.38	4	8982.8799	.9379	.32	4
8976.8931	.2821	.30	4	8982.8910	.9490	.36	4
8976.9014	.2904	.33	4	8982.9007	.9587	.38	4
8977.6021	.9911	.38	4	8982.9090	.9670	.36	4
8977.6076	0.9966	.39	4	8982.9153	.9733	.38	4
8977.6132	1.0022	.36	4	8982.9278	.9858	.58	3
8977.6194	1.0084	.32	4	8982.9347	.9927	.41	3
8977.6264	1.0154	.38	4	8982.9410	0.9990	0.26	1
8977.6326	1.0216	.38	4	8984.5708	1.2961	1.02	4
8977.6458	1.0348	.34	4	8984.5778	1.3031	1.15	4
8977.6507	1.0397	.39	4	8984.5854	1.3107	1.17	4
8977.6569	1.0459	.47	4	8984.5917	1.3170	1.23	4
8977.6632	1.0522	.43	4	8984.5972	1.3225	1.31	4
8977.6715	1.0605	.41	4	8984.6021	1.3274	1.31	4
8977.6771	1.0661	.36	4	8984.6111	0.0037	1.42	4
8977.7000	1.0890	.36	4	8984.6174	.0100	1.37	4
8977.7069	1.0959	.42	4	8984.6215	.0141	1.32	4
8977.7160	1.1050	.42	4	8984.6264	.0190	1.28	4
8977.7229	1.1119	.39	4	8984.6313	.0239	1.27	4
8977.7313	1.1203	.33	4	8984.6368	0.0294	1.20	4
8977.7389	1.1279	.36	4	8996.5722	1.3029	1.14	4
8982.5764	0.5344	.80	3	8996.5778	1.3085	1.26	4
8982.5840	.6420	.91	4	8996.5840	1.3147	1.29	4
8982.5889	.6469	.84	4	8996.5896	1.3203	1.30	4
8982.5938	.6518	.97	4	8996.5958	1.3265	1.49	4
8982.5993	.6573	.95	4	8996.6014	1.3321	1.37	4
8982.6049	.6629	.95	4	9003.6847	0.4190	0.45	5
8982.6167	.6747	.97	5	9003.6944	.4287	.31	4
8982.6264	.6844	.90	5	9003.7042	.4385	.28	1
8982.6319	.6899	.85	5	9003.7139	.4482	.32	3
8982.6375	.6955	.73	5	9003.7236	.4579	.30	2
8982.6438	.7018	.80	5	9003.7674	.5017	.43	3
8982.6486	.7066	.73	5	9003.7819	.5162	.39	4
8982.6681	.7261	.55	5	9003.7972	.5315	.52	3
8982.6743	.7323	.65	5	9003.8111	0.5454	0.45	3
8982.6806	.7386	.62	5	9008.5694	1.3055	1.14	4
8982.6861	.7441	.61	5	9008.5750	1.3111	1.18	4
8982.6917	.7497	.56	5	9008.5799	1.3160	1.26	4
8982.6972	.7552	.61	5	9008.5847	1.3208	1.31	4
8982.7201	.7781	.53	5	9008.5903	1.3264	1.34	4
8982.7257	.7837	.51	5	9008.5958	1.3319	1.39	4
8982.7326	.7906	.45	5	9008.6097	0.0131	1.39	4
8982.7389	.7969	.49	5	9008.6160	.0194	1.23	4
8982.7486	.8066	.41	5	9008.6222	.0256	1.29	4
8982.7570	.8150	.47	5	9008.6292	.0326	1.20	4
8982.7688	.8268	.39	5	9008.6347	.0381	1.10	4
8982.7757	.8337	.49	5	9008.6396	.0430	1.05	3
8982.8125	.8705	.41	5	9008.6590	.0624	0.97	4
8982.8208	.8788	.39	5	9008.6653	.0687	.88	4
8982.8285	0.8865	0.33	5	9008.6729	0.0763	0.70	3

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
9008.6785	0.0819	0.67	4	9015.8861	0.6259	0.68	4
9008.6847	.0881	.74	3	9015.8938	.6336	.80	4
9008.6903	.0937	.62	3	9015.9097	.6495	.84	4
9009.5674	.9708	.32	4	9015.9188	.6586	.80	4
9009.5729	.9763	.34	4	9015.9271	.6669	.83	4
9009.5778	.9812	.43	5	9015.9375	.6773	.87	4
9009.5833	.9867	.39	5	9015.9431	.6829	.81	4
9009.5889	.9923	.36	5	9015.9500	.6898	.80	3
9009.5944	0.9978	.38	5	9046.6972	.7842	.49	4
9009.6125	1.0159	.38	4	9046.7090	.7960	.48	4
9009.6181	1.0215	.38	4	9046.7160	.8030	.44	4
9009.6236	1.0270	.35	4	9046.7292	.8162	.47	4
9009.6285	1.0319	.37	4	9046.7368	.8238	.42	4
9009.6333	1.0367	.28	2	9046.7438	.8308	.48	4
9013.5792	0.9844	.39	3	9046.7792	.8662	.39	4
9013.5875	.9927	.40	3	9046.7861	.8731	.42	4
9013.5931	0.9983	.32	3	9046.7986	.8856	.34	4
9013.5986	1.0038	.37	3	9046.8056	.8926	.41	4
9013.6069	1.0121	.40	3	9046.8194	.9064	.27	3
9013.6139	1.0191	.34	3	9046.8257	.9127	.41	3
9014.6347	0.7072	.75	4	9047.5049	.2592	.40	4
9014.6410	.7135	.72	4	9047.5111	.2654	.37	4
9014.6465	.7190	.67	4	9047.5181	.2724	.47	4
9014.6528	.7253	.62	4	9047.5243	.2786	.43	4
9014.6597	.7322	.57	4	9047.5319	.2862	.43	4
9014.6674	.7399	.64	4	9047.5382	.2925	.40	4
9014.6729	.7454	.61	4	9047.5597	.3140	.41	4
9014.6799	.7524	.54	4	9047.5653	.3196	.41	4
9014.6861	.7586	.62	4	9047.5694	.3237	.49	2
9014.6944	.7669	.62	4	9047.5833	.3376	.45	2
9014.6986	.7711	.48	4	9047.5889	.3432	.48	2
9014.7042	.7767	.55	4	9047.5931	.3474	.41	2
9014.7556	.8281	.35	3	9047.6819	.4362	.48	3
9014.7722	.8447	.45	4	9047.6889	.4432	.37	3
9014.7792	.8517	.52	4	9047.7111	.4654	.38	3
9014.7896	.8621	.49	4	9047.7167	.4710	.42	3
9014.7986	.8711	.38	4	9047.7243	.4786	.40	3
9014.8063	.8788	.44	4	9047.7306	0.4849	0.38	3
9014.8326	.9051	.49	4	9052.5500	1.3061	1.24	3
9014.8417	.9142	.49	4	9052.5563	1.3124	1.21	3
9014.8528	.9253	.41	4	9052.5611	1.3172	1.38	3
9014.8590	.9315	.41	4	9052.5660	1.3221	1.35	3
9014.8667	.9392	.41	4	9052.5722	1.3283	1.44	3
9014.8736	.9461	.34	4	9052.6868	0.1102	0.72	4
9014.8896	.9621	.38	4	9052.6938	.1172	.57	4
9014.8965	.9690	.39	4	9052.7007	.1241	.49	3
9014.9035	.9760	.33	4	9052.7083	.1317	.43	3
9014.9132	.9857	.22	3	9052.7292	.1526	.48	4
9014.9208	0.9933	.29	3	9052.7354	.1588	.44	4
9014.9292	1.0017	.29	3	9052.7444	.1678	.37	3
9015.8514	0.5912	.54	4	9052.7507	.1741	.46	4
9015.8590	.5988	.60	4	9052.7570	.1804	.52	3
9015.8681	.6079	.69	4	9052.7632	.1866	.37	3
9015.8792	0.6190	0.78	4	9052.7688	0.1922	0.50	3

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
9052.7813	0.2047	0.48	3	9060.4688	1.2286	0.53	3
9053.4771	.9005	.45	4	9060.4757	1.2355	.55	3
9053.4847	.9081	.53	4	9060.4840	1.2438	.62	3
9053.4910	.9144	.49	3	9060.4903	1.2501	.59	3
9053.4972	.9206	.53	3	9060.4979	1.2577	.65	3
9053.5035	.9269	.51	4	9060.5035	1.2633	.74	3
9053.5111	.9345	.50	4	9060.5181	1.2779	0.96	3
9053.5340	.9574	.31	3	9060.5236	1.2834	1.02	3
9053.5403	.9637	.36	3	9060.5313	1.2911	1.08	3
9053.5472	.9706	.30	3	9060.5382	1.2980	1.22	3
9053.5542	.9776	.30	3	9060.5444	1.3042	1.20	3
9053.5597	.9831	.36	3	9060.5514	1.3112	1.29	3
9053.5660	.9894	.42	3	9060.6132	0.0403	1.06	4
9053.5743	0.9977	.39	3	9060.6201	.0472	0.96	4
9053.5806	1.0040	.46	2	9060.6299	.0570	1.01	4
9053.6326	1.0560	.40	2	9060.6368	.0639	0.90	4
9053.6403	1.0637	.35	2	9060.6431	.0702	.89	4
9053.6486	1.0720	.30	2	9060.6486	.0757	.90	3
9053.6618	1.0852	.43	3	9060.6688	.0959	.67	5
9053.6688	1.0922	.46	3	9060.6743	.1014	.61	5
9053.6750	1.0984	.45	3	9060.6806	.1077	.72	5
9053.6882	1.1116	.43	3	9060.6861	.1132	.70	5
9053.6944	1.1178	.56	2	9060.6931	.1202	.60	5
9053.7007	1.1241	.42	2	9060.7014	.1285	.53	5
9054.5118	0.6025	.76	3	9060.7236	.1507	.42	4
9054.5188	.6095	.80	3	9060.7306	.1577	.49	4
9054.5278	.6185	.89	3	9060.7389	.1660	.46	4
9054.5340	.6247	.77	3	9060.7458	.1729	.42	4
9054.5403	.6310	.87	3	9060.7556	.1827	.45	4
9054.5458	.6365	0.91	3	9060.7639	0.1910	.51	4
9054.5556	.6463	1.00	4	9061.5854	1.0125	.49	5
9054.5604	.6511	0.90	4	9061.5917	1.0188	.40	5
9054.5674	.6581	1.00	4	9061.5979	1.0250	.39	5
9054.5743	.6650	1.01	4	9061.6042	1.0313	.38	5
9054.6111	.7018	0.81	4	9061.6097	1.0368	.40	5
9054.6174	.7081	.79	4	9061.6153	1.0424	.44	5
9054.6361	.7268	.65	4	9061.6292	1.0563	.55	1
9054.6444	.7351	.52	4	9061.6340	1.0611	.43	5
9054.6507	.7414	.52	4	9061.6389	1.0660	.41	5
9054.6569	.7476	.59	4	9061.6451	1.0722	.44	5
9054.6653	.7560	.50	4	9061.6500	1.0771	.34	5
9054.6722	.7629	.51	4	9061.6576	1.0847	.43	5
9054.6951	.7858	.43	4	9061.6840	1.1111	.48	4
9054.7007	.7914	.48	4	9061.6896	1.1167	.48	4
9054.7083	.7990	.56	4	9061.6951	1.1222	.55	4
9054.7146	.8053	.54	3	9061.7021	1.1292	.44	4
9054.7208	.8115	.50	4	9061.7076	1.1347	.54	4
9054.7271	.8178	.51	4	9061.7139	1.1410	.52	4
9054.7597	.8504	.39	4	9061.7361	1.1632	.55	4
9054.7653	.8560	.41	4	9061.7417	1.1688	.58	4
9054.7708	.8615	.43	4	9061.7479	1.1750	.52	4
9054.7826	.8733	.44	4	9061.7535	1.1806	.48	4
9054.7889	.8796	.45	4	9061.7639	1.1910	.66	4
9054.7938	0.8845	0.49	4	9061.7694	1.1965	0.58	4

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
9061.7764	1.2035	0.58	4	9067.5458	0.3090	0.36	3
9061.7847	1.2118	.69	3	9067.5514	.3146	.34	3
9061.7903	1.2174	.70	3	9067.5569	.3201	.41	2
9061.7965	1.2236	.56	3	9067.6347	.3979	.44	5
9062.5528	0.6472	.87	3	9067.6403	.4035	.44	4
9062.5583	.6527	.83	3	9067.6465	.4097	.45	4
9062.5632	.6576	.88	3	9067.6528	.4160	.39	4
9062.5681	.6625	.85	3	9067.6583	.4215	.36	4
9062.5729	.6673	.86	3	9067.6903	.4535	.42	4
9062.5785	.6729	.98	3	9067.6958	.4590	.35	4
9062.6076	.7020	.85	4	9067.7014	.4646	.44	4
9062.6139	.7083	.72	4	9067.7097	.4729	.48	5
9062.6188	.7132	.69	4	9067.7153	.4785	.50	5
9062.6243	.7187	.58	4	9067.7208	.4840	.53	5
9062.6333	.7277	.73	4	9067.7340	.4972	.49	5
9062.6389	.7333	.68	4	9067.7403	.5035	.49	5
9062.6632	0.7576	.59	2	9067.7486	.5118	.51	5
9065.6174	1.0460	.39	3	9067.7570	.5202	.45	5
9065.6229	1.0515	.43	2	9067.7625	.5257	.51	5
9065.6292	1.0578	.39	4	9067.7694	.5326	.53	5
9065.6347	1.0633	.45	4	9067.7799	.5431	.53	5
9065.6500	1.0786	.47	4	9067.7889	.5521	.44	5
9065.6556	1.0842	.40	4	9067.7931	.5563	.47	4
9065.6604	1.0890	.42	4	9067.8049	.5681	.50	3
9065.6667	1.0953	.49	4	9067.8146	.5778	.58	3
9065.6736	1.1022	.50	4	9067.8215	.5847	.53	2
9065.6799	1.1085	.46	4	9070.6979	.7956	.45	4
9065.6924	1.1210	.46	4	9070.7028	.8005	.48	4
9065.6972	1.1258	.49	4	9070.7104	.8081	.48	4
9065.7035	1.1321	.50	4	9070.7194	.8171	.47	4
9065.7111	1.1397	.48	4	9070.7257	.8234	.47	4
9065.7160	1.1446	.51	4	9070.7361	.8338	.49	4
9065.7208	1.1494	.52	4	9070.7472	.8449	.42	5
9065.7299	1.1585	.46	4	9070.7528	.8505	.41	5
9065.7347	1.1633	.51	5	9070.7611	.8588	.39	5
9065.7396	1.1682	.51	5	9070.7660	.8637	.38	5
9065.7444	1.1730	.54	5	9070.7806	.8783	.40	5
9065.7493	1.1779	.52	5	9070.7861	.8838	.44	5
9065.7549	1.1835	.58	5	9078.4694	.5707	.51	3
9065.7681	1.1967	.54	4	9078.4750	.5763	.58	3
9065.7736	1.2022	.49	4	9078.4806	.5819	.58	3
9065.7826	1.2112	.58	3	9078.5174	.6187	.73	3
9065.7882	1.2168	.58	3	9078.5229	.6242	.74	3
9065.7944	1.2230	.51	3	9078.5285	0.6298	.73	3
9065.7993	1.2279	.55	3	9084.4736	1.2440	.64	3
9067.4611	0.2243	.46	5	9084.4806	1.2510	.73	3
9067.4667	.2299	.44	5	9084.4875	1.2579	.71	3
9067.4715	.2347	.42	5	9084.4958	1.2662	.80	3
9067.4764	.2396	.42	5	9084.5021	1.2725	0.95	3
9067.4819	.2451	.42	5	9084.5090	1.2794	1.00	3
9067.5194	.2826	.41	5	9084.5326	1.3030	1.14	4
9067.5250	.2882	.55	3	9084.5444	1.3148	1.29	5
9067.5306	.2938	.38	3	9084.5500	1.3204	1.35	5
9067.5375	0.3007	0.41	3	9084.5556	1.3260	1.53	5

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
9084.5611	1.3313	1.55	5	9096.6444	0.0876	0.63	5
9084.5674	0.0051	1.43	5	9096.6590	.1022	.64	5
9084.5792	.0169	1.36	5	9096.6646	.1078	.62	5
9084.5854	.0231	1.29	5	9096.6708	.1140	.66	5
9084.5951	.0328	1.27	5	9096.6764	.1196	.58	5
9084.6007	.0384	1.10	5	9096.6868	.1300	.59	5
9084.6083	.0460	1.07	5	9096.6931	.1363	.57	5
9084.6146	.0523	1.00	5	9098.5056	.6161	.81	4
9084.6417	.0794	0.90	4	9098.5118	.6223	.78	4
9084.6479	.0856	.70	4	9098.5438	.6543	.94	4
9084.6542	.0919	.73	4	9098.5500	.6605	0.99	4
9084.6611	.0988	.66	4	9098.5569	.6674	1.05	4
9084.6674	.1051	.65	4	9098.5632	.6737	0.96	4
9084.6736	.1113	.59	4	9098.5757	.6862	.92	4
9090.5285	.6353	.77	4	9098.5813	.6918	.86	4
9090.5368	.6436	.74	5	9098.5868	.6973	.81	3
9090.5431	.6499	.91	5	9098.6118	.7223	.70	3
9090.5521	.6589	.93	5	9098.6181	.7286	.68	3
9090.5583	.6651	.97	5	9098.6243	.7348	.69	3
9090.5639	.6707	.99	4	9098.6479	.7584	.61	3
9090.5792	0.6860	.92	3	9098.6535	.7640	.59	3
9092.5069	1.2810	0.95	4	9098.6597	.7702	.61	4
9092.5132	1.2873	1.03	4	9098.6757	.7862	.59	4
9092.5181	1.2922	1.09	4	9098.6826	.7931	.61	3
9092.5229	1.2970	1.06	4	9098.6917	0.8022	0.59	4
9092.5340	1.3081	1.25	5	9100.5333	1.3111	1.30	5
9092.5389	1.3130	1.31	5	9100.5396	1.3174	1.42	5
9092.5465	1.3206	1.46	5	9100.5472	1.3250	1.46	5
9092.5521	1.3262	1.51	5	9100.5542	1.3320	1.48	5
9092.5576	1.3317	1.50	5	9100.5590	0.0040	1.47	5
9092.5632	0.0046	1.50	5	9100.5653	.0103	1.38	5
9092.5729	.0143	1.36	4	9100.5771	.0221	1.32	4
9092.5785	.0199	1.32	4	9100.5833	.0283	1.26	4
9092.5847	.0261	1.18	4	9100.5896	.0346	1.18	4
9092.6167	.0581	0.95	4	9100.6181	.0631	0.96	4
9092.6222	.0636	.85	4	9100.6257	.0707	.78	3
9092.6278	0.0692	.76	5	9100.6444	0.0894	0.71	3
9096.5056	1.2815	0.90	5	9112.5278	1.3109	1.33	4
9096.5118	1.2877	1.00	5	9112.5333	1.3164	1.34	4
9096.5181	1.2940	1.00	5	9112.5444	1.3275	1.44	4
9096.5264	1.3023	1.21	5	9112.5507	0.0011	1.42	4
9096.5326	1.3085	1.28	5	9112.5569	.0073	1.46	4
9096.5396	1.3155	1.33	5	9112.5625	.0129	1.46	4
9096.5500	1.3259	1.44	5	9112.5736	.0240	1.27	4
9096.5556	1.3315	1.42	5	9112.5792	.0296	1.15	4
9096.5611	0.0043	1.49	5	9112.5840	.0344	1.21	4
9096.5674	.0106	1.40	5	9112.5965	.0469	1.01	4
9096.5771	.0203	1.35	5	9112.6028	.0532	1.00	4
9096.5840	.0272	1.20	5	9112.6097	0.0601	1.00	3
9096.5979	.0411	1.14	5	9116.5222	1.3071	1.25	5
9096.6035	.0467	1.12	5	9116.5292	1.3141	1.42	5
9096.6118	.0550	0.96	5	9116.5382	1.3231	1.49	5
9096.6181	.0613	.94	5	9116.5451	1.3300	1.51	5
9096.6389	0.0821	0.81	5	9116.5507	1.3356	1.49	5

TABLE I—*Continued*

H.G.M.T.	Phase	$a-v$	Wt.	H.G.M.T.	Phase	$a-v$	Wt.
	Days	Mag.			Days	Mag.	
9116.5569	0.0091	1.40	5	0502.5694	1.3129	1.10	.....
9120.5104	1.2971	1.10	5	0502.5785	1.3220	1.34	.....
9120.5181	1.3048	1.27	5	0502.5868	1.3303	1.34	.....
9120.5257	1.3124	1.25	5	0502.5944	0.0052	1.28	.....
9120.5333	1.3200	1.36	5	0502.6056	.0164	1.38	.....
9120.5417	1.3284	1.45	5	0502.6132	0.0240	0.88	.....
9120.5486	0.0026	1.47	5	0506.5132	1.2585	.77	.....
9120.5604	.0144	1.33	5	0506.5229	1.2682	.75	.....
9120.5674	.0214	1.35	5	0506.5319	1.2772	.87	.....
9120.5806	.0346	1.13	5	0506.5396	1.2849	0.93	.....
9120.5896	.0436	1.10	5	0506.5618	1.3071	1.14	.....
9120.5979	.0519	0.97	5	0506.5785	1.3238	1.35	.....
9120.6063	0.0603	.89	5	0506.5903	0.0029	1.43	.....
J.D. 242+				0506.5965	.0091	1.28	.....
0502.4826	1.2261	.76	.....	0506.6090	.0216	1.16	.....
0502.4910	1.2345	.70	.....	0506.6146	0.0272	1.21	.....
0502.4958	1.2393	.42	.....	0507.8660	1.2786	0.82	.....
0502.5014	1.2449	.54	.....	0507.8736	1.2862	0.97	.....
0502.5118	1.2553	.63	.....	0507.8806	1.2932	1.00	.....
0502.5236	1.2671	.90	.....	0507.8882	1.3008	1.05	.....
0502.5424	1.2859	.82	.....	0507.9000	1.3126	1.23	.....
0502.5500	1.2935	.94	.....	0507.9062	1.3188	1.36	.....
0502.5590	1.3025	0.90	.....	0507.9146	1.3272	1.31	.....
0502.5653	1.3088	1.06	.....	0507.9222	0.0021	1.36	.....

were combined into the eighty-two normals of Table II by forming weighted means for eight consecutive observations after arranging the differences $a-v$ in order of phase. The observations of 1915 have not been used in the solution because they are few in number and greatly separated in time from the others.

The resulting light-curve (Fig. 1) shows a primary eclipse of depth 1.09 mag. and duration about 8^h, and a secondary eclipse of depth 0.57 mag. and apparently slightly shorter duration. The curve between eclipses has the pronounced arch of the β Lyrae type, indicating decidedly ellipsoidal stars. Near secondary it appears a little higher than near primary minimum, possibly the result of a reflection effect of radiation from the brighter star upon the adjacent side of the fainter.

In accordance with Russell's method, which was used for the solution, the differences in magnitude were reduced to intensities l, unit value for which was assumed to correspond to 1 when $a-v=0.360$

TABLE II

WEIGHTED NORMALS OF LIGHT-CURVE

Phase	$a-v$	O.−C.	O.−C′.	Phase	$a-v$	O.−C.	O.−C′.
Days	Mag.	Mag.	Mag.	Days	Mag.	Mag.	Mag.
0.0011	1.464	+0.020	+0.018	0.7586	0.555	−0.003	+0.029
.0080	1.402	+ .006	+ .004	.7716	.532	+ .019	+ .047
.0148	1.326	+ .003	.000	.7843	.489	− .003	+ .020
.0213	1.272	+ .017	+ .019	.7946	.488	+ .015	+ .031
.0289	1.206	+ .036	+ .037	.8052	.482	+ .024	+ .030
.0370	1.085	+ .003	+ .002	.8161	.475	+ .031	+ .032
.0466	1.024	+ .029	+ .025	.8275	.440	+ .002	+ .002
.0566	0.947	+ .038	+ .030	.8441	.429	+ .001	+ .002
.0642	.859	+ .011	+ .002	.8562	.427	+ .005	+ .005
.0758	.773	+ .004	− .006	.8709	.408	− .004	− .004
.0844	.707	− .008	− .020	.8845	.408	− .002	− .002
.0976	.658	+ .010	− .004	.9043	.402	+ .005	+ .003
.1097	.621	+ .025	+ .010	.9168	.425	+ .033	+ .033
.1229	.548	.000	− .010	.9316	.399	+ .012	+ .012
.1464	.491	− .002	− .004	.9508	.373	− .009	− .009
.1736	.432	− .035	− .035	.9679	.352	− .028	− .028
.2040	.432	− .012	− .012	.9798	.385	+ .005	+ .005
.2412	.403	− .014	− .014	.9888	.385	+ .006	+ .006
.2754	.413	+ .015	+ .015	0.9967	.356	− .025	− .025
.3004	.381	− .006	− .006	1.0106	.397	+ .013	+ .013
.3638	.393	+ .013	+ .013	1.0248	.365	− .020	− .020
.4078	.390	− .001	− .001	1.0417	.414	+ .021	+ .021
.4370	.376	− .027	− .027	1.0577	.405	+ .003	+ .003
.4608	.391	− .025	− .025	1.0763	.403	− .006	− .006
.4808	.454	+ .025	+ .025	1.0912	.435	+ .013	+ .013
.5145	.479	+ .031	+ .033	1.1081	.455	+ .021	+ .021
.5462	.463	− .036	− .012	1.1215	.441	− .002	− .002
.5746	.539	− .038	− .005	1.1407	.496	+ .044	+ .044
.6018	.652	− .018	+ .005	1.1684	.523	+ .041	+ .041
.6184	.731	− .010	+ .003	1.1871	.549	+ .042	+ .038
.6307	.785	− .020	− .020	1.2133	.593	+ .017	+ .002
.6439	.845	− .011	− .025	1.2433	.627	− .086	− .097
.6518	.899	+ .010	− .019	1.2733	0.915	− .015	− .022
.6591	.922	+ .011	− .029	1.2899	1.045	− .031	− .032
.6682	.941	+ .031	− .009	1.3003	1.185	− .003	− .002
.6833	.885	+ .031	+ .017	1.3059	1.240	− .013	− .011
.6958	.812	+ .013	+ .015	1.3101	1.304	+ .006	+ .005
.7076	.711	− .034	− .023	1.3146	1.328	− .018	− .022
.7218	.655	− .031	− .009	1.3196	1.377	− .023	− .025
.7330	.610	− .032	− .006	1.3242	1.438	+ .003	+ .001
0.7469	0.575	−0.020	+0.012	1.3288	1.460	+0.012	+0.011

mag. The light-intensities outside the eclipses were then plotted and represented by the expression

$$l=a-s\cos\theta-\tfrac{1}{2}z\cos^2\theta\ ,$$

where a is the maximum intensity, $2s$ the difference in intensity of the two sides of the fainter star, θ the phase angle, and $z=\epsilon^2\sin^2 i$,

ϵ being the eccentricity of the ellipsoidal stars. Approximate values of the constants were found to be

$$a=0.980, \qquad s=0.026, \qquad \tfrac{1}{2}z=0.140 .$$

A correction by least squares gave

$$a=0.9808, \qquad s=0.0247, \qquad \tfrac{1}{2}z=0.1434 ,$$

which reduced the sum of the squares of the residuals from 119 to

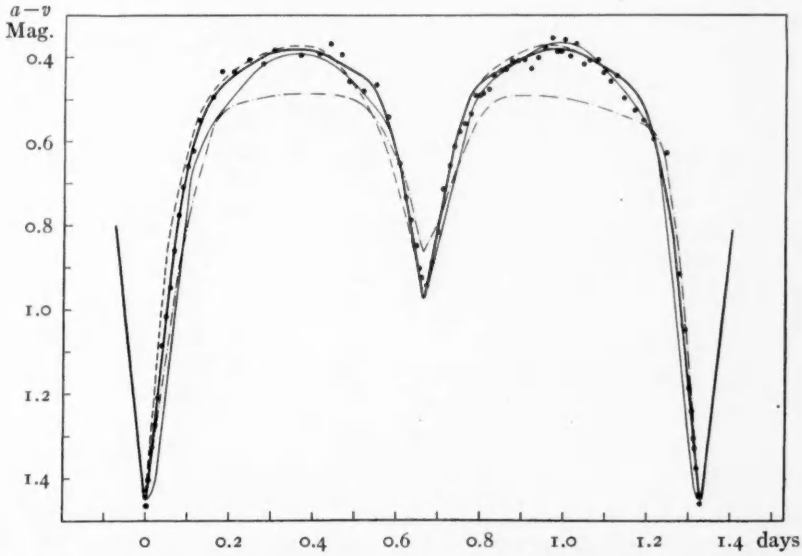

FIG. 1.—Photometric observations and light-curves of TT Aurigae. The dots are the Princeton observations by Joy. The heavy curve is computed from the uniform elliptical solution derived in this investigation. The light line represents the photographic observations of Martin and Plummer; the dot-and-dash curve, Jordan's photographic observations; and the dash curve, Balanowsky's observations with the Zöllner photometer. These curves have been shifted so that the primary minima coincide with that observed at Princeton.

101. The intensities of all the normals were then rectified by the formula

$$l'=\frac{l+0.025(1+\cos\theta)+0.143\, l\cos^2\theta}{0.981+0.025},$$

which reduced the intensity at maximum of the rectified curve to 1.

The rectified eclipse-curves are different in shape, the secondary being distinctly steeper and narrower than the primary, except near the top. It was thought that darkening at the limbs of the stars might account for this; but in the first solution the difference was ignored, only the shape of the primary (which is better defined than the secondary) and the two depths being taken into account. The resulting elements I appear in Table III, and the residuals O.−C. are given in Table II. They might be varied in the direction of

TABLE III

PHOTOMETRIC ORBITAL ELEMENTS

	I Uniform Circular	II Uniform Elliptical	Balanowsky
e, orbital eccentricity	0.00	0.09	0.048
ω, longitude of periastron	....	270°	262°.3
i, inclination	87°.1	88°.4	88°.3
k, ratio of radii	0.90	0.90	0.84
r_1, longer radius, large star	.38	.36	.307
r_2, longer radius, small star	.34	.32	.244
b_1, shorter radius, large star*	.32	.31	.258
b_2, shorter radius, small star*	.29	.27	.205
b/r, ellipticity of stars	.84	.86	.840
L_1, light of large star	.68	.66	.734
L_2, light of small star	0.32	0.34	0.266
J_1/J_2, ratio of mean surface brightness	1.68	1.56	1.95
$2s$, difference in intensity of two sides of fainter star	0.05	0.05	....
Primary eclipse	Partial, a_0= 0.975, small star in front	Grazing, annular	Annular

* Disregarding polar flattening (*Contributions from Princeton University Observatory*, No. 3, 116, 1915).

closer equality of diameters and a slightly smaller inclination by favoring the curve of the secondary minimum at the expense of that of the primary, but the possible changes would be small. A second solution, attempting to account for the discrepancy in shape by introducing darkening at the limb, was unsuccessful; no set of elements could be found which came near to reproducing the curve forms of both minima.

It was therefore decided to introduce eccentricity into the orbit. The secondary minimum is midway between primary minima, but the observations indicate that it is of shorter duration. Hence, periastron must occur at the time of secondary minimum. The spectro-

scopic observations are not inconsistent with a small eccentricity with the line of apsides perpendicular to the line of nodes, but on account of the quality of the spectrum it appears impossible to determine the amount of the eccentricity from these observations. A few approximations show that except at the shoulders of the curve, which are poorly defined anyway, an orbital eccentricity around 0.09, with periastron at secondary (270° long.), would give a much better fit for secondary minimum than the circular elements, and an equally good fit for primary minimum. The adopted solution gave elements II in Table III and the residuals O.−C′. of Table II. For the whole series of observations the probable error of a normal place (eight observations) is 0.015 mag. and that of a single observation of average weight (3.9) is 0.043 mag. These values are of the same order as have been found by Dugan and others who have used the Princeton photometer and similar methods of solution.

It is instructive to compare these elements with those of Balanowsky (also in Table III). His smaller orbital eccentricity was obtained not from the width of his secondary minimum, but from the maximal and minimal points of his observed curve, reflection effect being neglected; but his secondary minimum, though not very definite in shape, is perceptibly narrower than his primary. His observed ranges of variation are very close to those of Joy, but his minima are a little narrower and he used a larger value of z, thus obtaining smaller rectified ranges and smaller and more unequal stars. The observed strength of the lines of the secondary star in the spectrograms favors the results found here. However, the general resemblance of the two solutions from entirely independent sources is satisfactory. The shape of primary minimum and the depths fix k, r, and i fairly definitely. Darkened elements are less satisfactory and are not given.

Unfortunately, the two published photographic curves are at variance with the visual curves and with each other, as is apparent from Figure 1. Martin and Plummer's primary minimum is steep with a flat bottom, while Jordan's is narrower, more pointed, and asymmetrical. Joy, Balanowsky, and Martin and Plummer agree fairly well on the form of the curve outside eclipse and on the depths

of minima; but Jordan's curve outside eclipse is much flatter than the others, and his secondary minimum 25 per cent shallower.

III. SPECTROGRAPHIC OBSERVATIONS AND ORBIT

From 1917 to 1930 thirty-two spectrograms of TT Aurigae were obtained by Joy at Mount Wilson as listed in Table IV. The spectral type of the brighter star is B3. The lines are so wide and indefinite that it is nearly impossible to measure them with any accuracy. The rotational effect from limb to limb is 340 km/sec. The spectrum of the companion is clearly present at the time of maximum separation of the lines and is about one-half as strong as that of the primary. It seems to be similar in type to that of the principal star. Spectrogram C 5392 was exposed during primary eclipse especially to show the spectrum of the fainter star, but no difference in type could be detected when the spectra of the two stars were compared. The eclipse, however, is not total. Since only 80 per cent of the brighter star is covered at maximum of eclipse, its light may mask that of the smaller star to some extent.

The H and K lines of both components are faint, but are visible under the best conditions. They have been measured on nine of the plates.

The lines of interstellar calcium are present in fair strength and can be accurately measured on plates correctly exposed. Velocities from these lines, reduced to the sun, and their weights are given in the last two columns of Table IV. The weighted mean velocity for the interstellar calcium lines measured on eighteen plates is +4.3 km/sec., which is approximately the value, with reversed sign, of the solar motion (7.0 km/sec.) in that direction.

The measures are plotted in Figure 2. The smaller circles represent the primary and the larger the secondary. The velocities of stationary H and K are represented by crosses. The curve is drawn on the basis of a circular orbit.

No attempt was made to distribute the observations over the whole of the velocity-curve but rather to confine them to times of maximum in order to determine the range and masses of the com-

TABLE IV

SPECTROGRAPHIC OBSERVATIONS

Plate	J.D. 242+	Phase	Velocity			Interstellar Calcium	
			Primary	Secondary	Wt.	H and K	Wt.
		Days	km/sec.	km/sec.		km/sec.	
C 5392......	6018.774	0.007	....	+ 5	1	+16.1	2
γ 5543......	1267.658	.081	−114	+112	1	....	....
C 3092......	4123.854	.232	−188	+181	1	+ 9.5	4
γ 6523......	1595.754	.324	−183	+245	2	−11.1	1
7657......	1944.931	.325	−184	+218	1	....	....
C 274......	2360.743	.326	−169	+245	1	....	....
3709......	4571.750	.330	−176	+215	1	+11.2	2
γ 6439......	1567.772	.330	−170	+226	3	−14.4	2
6726......	1655.736	.334	−154	+256	2	....	....
C 177......	2268.797	.338	−187	+277	2	+ 5.0	3
3660......	4539.774	.340	....	....	....	+12.4	2
685......	2597.993	.349	−174	+303	1	+12.8	2
2576......	3770.823	.375	−224	+253	1	+ 4.1	2
3038......	4068.022	.375	−168	+282	1	+15.1	1
885......	2740.642	.396	−249	+240	1	....	....
γ 5577......	1270.658	.415	−228	+246	1	....	....
C 4533......	5192.892	.419	−207	+305	2	− 4.3	3
325......	2395.719	.650	+ 1	....	3	....	....
607......	2561.010	.683	+ 40	....	1	....	....
γ 6431......	1566.794	.685	+ 11	....	2	+13.8	3
C 4509......	5183.837	.693	0	....	3	....	....
2572......	3769.825	.710	+ 21	....	1	−18.0	1
3070......	4097.878	.911	+214	−208	2	+ 8.9	4
4099......	4834.953	.985	+195	−208	1	....	....
168......	2266.785	.991	+160	−225	1	....	....
1633......	3135.728	.993	+204	−221	2	....	....
675......	2595.973	0.994	+218	−239	1	....	....
4595......	5246.792	1.009	+227	−265	3	− 2.0	3
5398......	6019.793	1.026	+182	−252	3	+ 9.8	4
227......	2330.806	1.041	+225	−252	2	....	....
2617......	3800.819	1.051	+175	−280	1	−17.0	2
942......	2766.661	1.093	+183	−210	1	− 1.1	2

ponents. After weighting and combining the observations, the elements

$$
\begin{aligned}
e &= 0.0 \text{ (assumed)} & a_1 \sin i &= 3{,}600{,}000 \text{ km} \\
\gamma &= +10.2 \text{ km/sec.} & a_2 \sin i &= 4{,}500{,}000 \\
K_1 &= 196.8 & m_1 \sin^3 i &= 6.7 \odot \\
K_2 &= 246.1 & m_2 \sin^3 i &= 5.3
\end{aligned}
$$

were found. The probable error of a single observation is very large, as might be expected from the character of the spectrum.

IV. ABSOLUTE DIMENSIONS

The photometric and spectroscopic results may be combined to obtain the absolute dimensions of the system. The primary eclipse is produced when the smaller star, which is also less massive and of lower surface brightness, passes in front of the larger, more mas-

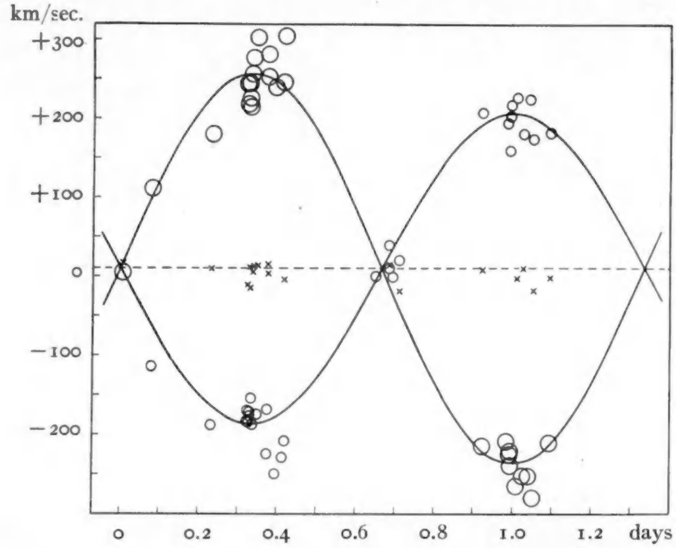

FIG. 2.—Velocity-curve of TT Aurigae. The small and large circles represent the observations of the primary and secondary, respectively. The crosses give the radial velocities of interstellar calcium relative to the sun.

sive star. The following values for the circular elements are thus determined:

a_1, semi-major axis of primary orbit	3,600,000 km
a_2, semi-major axis of secondary orbit	4,500,000
a_1+a_2, semi-major axis of relative orbit	8,100,000
r_1, longer radius of large star	3,100,000 (4.5 ☉)
r_2, longer radius of small star	2,800,000 (4.0)
b_1, shorter radius of large star	2,600,000 (3.7)
b_2, shorter radius of small star	2,300,000 (3.3)
m_1, mass of large star	6.7 ☉
m_2, mass of faint star	5.3
ρ_1, density of large star	0.11 ☉
ρ_2, density of faint star	0.12
M_1, absolute magnitude of large star	−1.2 mag.
M_2, absolute magnitude of small star	−0.9
π, parallax	0″001

The absolute magnitudes are derived from the formula

$$M=\frac{29,500}{T}-5\log r-0.08\ .$$

The temperatures are taken to be 15,000°. If the temperature of the fainter star were assumed to be 12,000° instead of 15,000°, its absolute magnitude would become −0.4, which would satisfy the light ratio of the two stars found in the photometric solution. The parallax is determined for the brighter star by using the absolute magnitude (−1.2) and apparent magnitude (8.9). An absolute trigonometric parallax of −0.″003 has been found at the Yerkes Observatory.[1]

The stars are quite normal in every way. The masses and luminosities are in fair agreement with Eddington's mass-luminosity relationship.

Our thanks are especially due to Professor Russell and Professor Dugan of Princeton University, through whose interest and encouragement this investigation was begun and finally brought to completion.

Carnegie Institution of Washington
Mount Wilson Observatory
August 1930

[1] *Astronomical Journal*, **37**, 44, 1926.

ON THE ORIGIN OF BRIGHT LINES IN SPECTRA OF STARS OF CLASS B

By OTTO STRUVE

ABSTRACT

It is found that stars of class B, having *widely separated double bright lines* are characterized by extremely flat and broad absorption lines *suggestive of rapid axial rotation*, of the order of several hundred km/sec. Stars having narrow, single emission lines, few in number, show little rotation.

The suggestion is now offered that rapidly rotating single stars of spectral class B are unstable, and form *lens-shaped bodies which eject matter at the equator*, thus forming a *nebulous ring* which revolves around the star and gives rise to emission lines. The inclination of the star's axis would then be responsible for the observed range in width of the emission lines.

I. INTRODUCTION

The appearance of emission lines in spectra of stars of class B has not heretofore been satisfactorily explained. It has been recently shown by E. A. Milne[1] that Sir Arthur Schuster's work on the effect of scattering in a stellar atmosphere does not account for these lines. The results of S. Rosseland[2] are more promising; they seem to explain the mechanism responsible for the excitation of bright lines. It has, however, not been understood why only certain B-type stars show bright lines, while other stars of similar spectral type have only absorption lines.

The observational results[3] available at present are, briefly, as follows:

1. Bright lines occur in all spectral types, but chiefly at the two ends of the spectral sequence.

2. In the early type stars, bright $H\alpha$ is the strongest member of the Balmer series, and the intensity decreases rapidly toward the limit; in the M stars, however, $H\delta$ is the strongest. Stars of intermediate type occasionally show bright borders on the red sides of absorption lines of hydrogen (ϵ Aurigae). It is believed that the

[1] *Monthly Notices of the Royal Astronomical Society*, **89**, 15, 1928; A. Pannekoek, *Handbuch der Astrophysik*, **3**, Part I, 348, 1930.

[2] *Astrophysical Journal*, **63**, 218, 1926.

[3] For more complete summaries see the original papers by P. W. Merrill, R. H. Curtiss, etc.

bright lines in these groups of stars do not have the same origin. This paper deals exclusively with the Be stars.

3. In the early spectral types the greatest number of stars having emission lines is found in subdivision B3. The frequency decreases rapidly toward the later types, especially after B5. The greatest proportion of stars having emission lines is found in class O, as is shown by Table I, published by the late R. H. Curtiss.[1]

4. The emission lines in B-type stars may be divided into two groups: (*a*) single bright lines centrally superposed over normal

TABLE I

Class	No. of *H.D. Catalogue* stars	Emission-Line Stars	Ratio
O_5-O_9	55	7	1:8
B_0-B_5	1996	136	1:15
B_8	1604	13	1:123
B_9	2752	3	1:917
A_0	6320	1	1:6320

absorption lines; (*b*) double bright lines symmetrically placed on both sides of the normal wave-length.

5. The widths of the single lines, as well as the distances between the components of the double lines, are not the same for all stars; in the case of $H\beta$ they range from about 1 A to more than 10 A. No emission lines are known in B stars that are as narrow as the bright lines in the spectra of diffuse gaseous nebulae.

6. The widths of the emission lines, defined as the distance between the steepest outer gradients of emission, show according to R. H. Curtiss[2] a pronounced proportionality to wave-length. The width of any hydrogen emission line is given by

$$\Delta\lambda = 6.28\times10^{-4}(\lambda-3270)(W-2.61)+2.61 ,$$

where W is the measured width of $H\beta$.

7. The emission lines are frequently subject to change in intensity and two distinct types of this variation are discerned: in some stars

[1] *Journal of the Royal Astronomical Society of Canada*, **20**, 23, 1926.

[2] *Publications of the Observatory of the University of Michigan*, **3**, 1, 1923.

the total amount of energy in the emission lines changes (Pleione, κ Draconis); in others the relative intensities of the two bright components vary periodically (π Aquarii), the total energy remaining approximately constant. The periods are usually long—often several years in duration. In many cases periods have not yet been established.

8. There are peculiar stars showing rapid changes in the emission lines (β Lyrae, ϕ Persei); these are usually known to be spectroscopic binaries.

9. Stars like P Cygni have emission lines with strongly displaced absorption lines on their violet sides. These stars are almost certainly related to the novae, and will not be discussed in this paper.

10. The emission lines are usually due to hydrogen. In several cases bright lines of ionized iron and of other elements have also been observed.

11. According to B. P. Gerasimovič[1] and to R. H. Curtiss,[2] the Be stars are more luminous than the normal B's. This is supported by the fact that the interstellar *Ca* II lines in Be stars are, on the average, abnormally strong.[3] Great luminosity probably implies also great mass.

II. NEW OBSERVATIONAL RESULTS

The most outstanding fact about the bright-line stars is that they form a group running parallel to the normal sequence of stellar spectra. But the theory of ionization accounts so satisfactorily for even small changes in the intensities of stellar absorption lines that the occurrence or non-occurrence of bright lines must be attributed to real structural differences among the stars, and not to changes in the conditions of excitation. In analogy with the novae and with the Wolf-Rayet stars, it is natural to attribute the bright lines to an outer gaseous envelope, or nebula.[4] But in the novae the nebulous material is receding from the star, as has been proved by direct observation in the case of Nova Aquilae 1918.[5] The much greater

[1] *Harvard College Observatory*, Bull. 849, p. 8, 1927.

[2] *Journal of the Royal Astronomical Society of Canada*, **20**, 35, 1926.

[3] O. Struve, *Astrophysical Journal*, **67**, 376, 1928.

[4] C. S. Beals, *Monthly Notices of the Royal Astronomical Society*, **90**, 202, 1929; D. H. Menzel, *Publications of the Astronomical Society of the Pacific*, **41**, 344, 1929.

[5] E. P. Hubble and J. C. Duncan, *Popular Astronomy*, **38**, 598, 1930.

stability of the phenomena observed in Be stars and especially the absence of absorption on the violet sides of the emission lines suggest that the nebula in a Be star is a permanent feature in approximate stability. But why do not all B stars have such nebulae around them? The answer is found, it seems to me, in the spectra of the Be stars.

In Table II are listed the majority of the known or suspected Be stars for which spectrograms are available in the collection of the Yerkes Observatory. The last column contains a brief description of the emission lines. Column 6 gives an estimate of the width of the ordinary stellar absorption lines other than those of hydrogen. Number 10 designates, on an arbitrary scale, a star with extremely "dish-shaped" absorption lines, which are so nebulous that they can hardly be seen; 5 denotes a line corresponding to an average equatorial rotation of 60–70 km/sec. Perfectly sharp lines are denoted by 0. From our former studies of stellar spectra it is known that "dish-shapedness" is a criterion of axial rotation, measuring the component, in the line of sight, of the equatorial velocity of the star's rotation. For this reason column 6 is headed "Rotation."

It is at once apparent that the majority of these stars rotate rapidly. Excessive rotations, estimated at 9 or 10 (believed to correspond to components in the line of sight of 250 km/sec. or more), are frequent. Apparently bright lines occur preferentially in stars having rapid axial rotation.

Rotations of 5 or less are invariably associated with narrow emission lines. In Table III, I have grouped the stars roughly according to the widths of the emission lines. It is again clear that the narrow emission lines are associated with comparatively small rotational components.

This result is further substantiated by Table IV, in which I have listed all stars for which R. H. Curtiss[1] has measured the widths of the emission lines.

Finally in Table V are Merrill's observations.[2] All stars showing double bright $H\beta$ are classified by him as having "nebulous" absorption lines, and the only two stars with "sharp" lines have single

[1] *Publications of the Observatory of the University of Michigan*, **3**, 1, 1923.

[2] Merrill, Humason, and Burwell, *Astrophysical Journal*, **61**, 389, 1925.

TABLE II

LIST OF BE STARS

Star	α	δ	Mag.	Sp.	Rotation	Description of Bright $H\beta$
27 γ Cass	0:50	+60:11	2.2	Bp	10	Very broad single, with central absorption
54 ϕ Per	1:37	+50:11	4.2	B0p	10	Broad double
1 Hev. Cam	3:11	+65:17	4.8	B3p	7	Broad double
ψ Persei	3:29	+47:51	4.3	B5p	9	Broad double
17 Tauri	3:39	+23:48	3.8	B5	....	No bright lines on our plates
23 d Tauri	3:40	+23:38	4.2	B5	10	Broad double
25 η Tauri	3:42	+23:48	3.0	B5	7	Broad double, but very faint
27 f Tauri	3:43	+23:45	3.8	B8p	....	No bright lines on our plates
48 c Persei	4:01	+47:27	4.0	B3p	5	Narrow single
9 Camelop	4:44	+66:10	4.4	B0	4	Emission hardly visible in $H\beta$
11 Camelop	4:57	+58:50	5.3	B3p	2	Narrow single
25 Orionis	5:20	+ 1.45	4.7	B3p	7	Double
120 Tauri	5:28	+18:29	5.5	B3p	9	Broad double; poor plate
43 θ^2 Orionis	5:30	− 5:29	5.2	B1	....	Orion nebula
123 ζ Tauri	5:32	+21:05	3.0	B3	7	Broad double
47 ω Orionis	5:34	+ 4:04	4.5	B3p	5	Very faint double
62 χ^2 Orionis	5:58	+20:08	4.7	B2p	0	No bright lines on our plates
−6° 1391 Monoc	5:59	− 6:42	5.1	B2p	7	Double
−11° 1460 Mon	6:17	−11:44	5.5	B2p	6	Very broad single
18 ν Gemin	6:23	+20:17	4.1	B5	8	Two very faint bright components far apart
11 β Monoc. A	6:24	− 6:58	4.7	B3p	7	Broad double, strong
11 β Monoc. B	6:24	− 6:58	5.2	B3p	6	Narrow double
11 β Monoc. C	6:24	− 6:58	5.7	B3p	7	Broad double
28 ω Can. Maj	7:11	−26:35	3.8	B3p	5	Narrow single
3 β Can. Min	7:22	+ 8:29	3.1	B8	10	Two faint components far apart
5 κ Drac	12:29	+70:20	3.9	B5p	8	Narrow double
7 χ Ophiuchi	16:21	−18:14	4.8	B3p	6	Narrow single
10 β Lyrae	18:46	+33:15	Var.	B2p	....	Peculiar—omitted
46 υ Sagittar	19:16	−16:08	4.4	B8p+F2p	....	Composite—omitted
39 κ Aquilae	19:32	− 7:15	5.0	B0	....	Probably not bright
28 b² Cygni	20:06	+36:33	4.8	B2	9	Double
34 P Cygni	20:14	+37:43	4.9	B4p	0	Peculiar, nova—omitted
54 λ Cygni	20:44	+36:08	4.6	B5	4	Not bright on our plates
+46° 3111 Cygni	20:52	+47:02	5.9	B8p	0	Very narrow double; only one plate—uncertain
59 f¹ Cygni	20:56	+47:08	4.9	B0p	9	Unequal broad double
60 Cygni	20:58	+45:46	5.2	B3	8	Broad double, faint
66 υ Cygni	21:14	+34:29	4.4	B3p	4	Rather narrow single
6 Cephei	21:17	+64:27	5.2	B3p	6	Very narrow double
39 ϵ Capricor	21:32	−19:54	4.7	B5p	7	Peculiar double bright; *He* and *Mg* give rotation 7, but many metallic lines give rotation 0
9 Cephei	21:35	+61:38	4.9	B2p	....	Not bright on our plates
+56° 2617 Cephei	21:36	+57:02	5.6	Oe5	....	Not bright on our plates
31 o Aquarii	21:58	− 2:38	4.7	B5p	10	Very broad double
31 Pegasi	22:17	+11:42	4.9	B3p	3	Single
52 π Aquarii	22:20	+ 0:52	4.6	B1p	10	Broad double
ϵ Pisc. Austr	22:35	−27:34	4.2	B8	....	Not bright on our plates
4 β Piscium	22:59	+ 3:17	4.6	B5p	1	Very narrow single
8 Lacertae	22:31	+39:07	5.4	B3p	8	Average single

TABLE III

Group	Width of Emission Lines	No.	Rotation
I	Double, very broad	15	8.5
II	Double, average and single, very broad	7	7.3
III	Double, narrow and single, average	6	5.3
IV	Single, very narrow	6	3.7

emission lines. In the Mount Wilson classification for normal stars[1] the proportion of "n" to "s," in the range B0–B5, is about 2 to 1. The preponderance of rapid rotation, especially among stars with double emission lines, is therefore well substantiated.

It is reasonable to suppose that the correlation between width of emission and degree of rotation depends upon the inclination of

TABLE IV

Star	Rotation	Width of $H\beta$
f^1 Cygni	9	10.5 A
π Aquarii	10	7.5
ϕ Persei	10	7.0
1 Hev. Cam.	7	6.5
β Mon.	7	6.5
b^2 Cygni	9	6.0
ψ Persei	9	6.0
κ Drac.	8	5.0
γ Cass.	10	5.0
c Persei	5	4.0
β Piscium	1	2.5
11 Camelop.	2	1.0

TABLE V

		Single Bright $H\beta$	Double Bright $H\beta$
No. of stars according to Merrill	"n"	5	8
	"s"	2	0

the axis. Apparently rapid axial rotation sponsors the occurrence of wide emission lines. When the inclination is close to zero, the emission lines appear narrow.

This interpretation is also in agreement with the relative frequencies of the rotational components in Table II. Large values predominate. This, of course, is what would be expected. The probability of an inclination between i_1 and i_2 is proportional to $(\cos i_1 - \cos i_2)$. This readily explains the predominance of large values in column 6 of Table II.

[1] Adams and Joy, *ibid.*, **57**, 294, 1923.

III. DISCUSSION

Our observational result, that all stars with broad double emission lines show "dish-shaped" absorption lines of extreme flatness, suggests that the two phenomena are related; rapid rotation seems to be prerequisite to the appearance of bright lines. In a former paper[1] I have shown that there are single stars which have such enormous rotational velocities that they are in danger of becoming unstable. Just what happens if a star does become unstable because of excessive angular momentum we do not know. Fission, if it occurs at all, is one means of relieving the system of its excess of momentum. But there is another possibility. Sir James Jeans has shown that under certain conditions a rapidly rotating gaseous body may become lens shaped and throw off matter at its sharp equatorial edge.[2] It is therefore reasonable to expect that B stars in extremely rapid rotation will eject gaseous matter at the equator. A gaseous ring will be formed and the system will resemble in appearance the planet Saturn. The ring will consist of separate atoms which revolve around the central body according to the law of gravitation.

It should be noted that radiation pressure will make the star even more unstable than purely mechanical considerations would indicate.[3] Selective radiation pressure—which alone would come into consideration—acts differently upon different elements, and may explain the predominance of hydrogen and ionized iron in the bright-line spectrum.

If the inclination of the nebulous ring revolving around the star is 90° we observe two bright components superposed upon the normal stellar absorption line. In order to obtain an idea of the theoretical contour of the emission line, we proceed in the following manner. If the inclination of the ring is i, and the orbital velocity within the ring is v, and if, furthermore, the ring is sufficiently thin to permit us to neglect the difference of v between inner and outer circumference, then the radial velocity at any point is

$$\rho = v \sin i \sin \theta \ ,$$

[1] *Ibid.*, **72**, 1, 1930.

[2] *Astronomy and Cosmogony*, p. 257, 1928.

[3] I am indebted for this idea to Dr. Edison Pettit.

where θ is the angle at the star between the line of sight and the direction toward the point. From two points we have

$$\theta_1-\theta_2=\text{arc sin}\left(\frac{\rho_1}{v \sin i}\right)-\text{arc sin}\left(\frac{\rho_2}{v \sin i}\right) .$$

We make the steps $(\rho_n-\rho_{n-1})$ sufficiently small to consider all atoms between θ_n and θ_{n-1} as having the same velocity of $(\rho_n+\rho_{n-1})/2$. Then the intensity at this point is const. $(\theta_1-\theta_2)$. Since our ring is

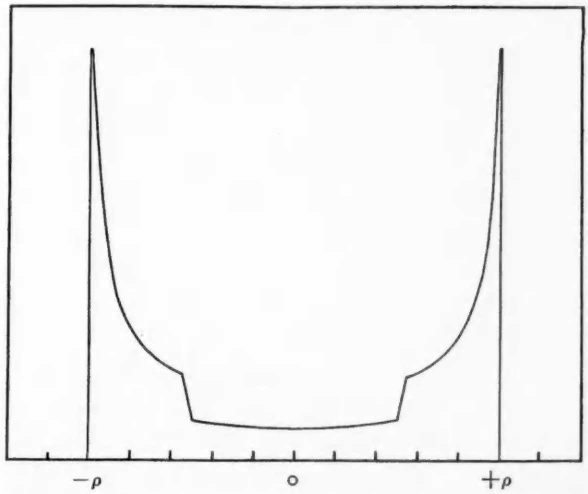

FIG. 1.—Simplified theoretical contour of emission lines in Be stars

circular, each value of $C.\ (\theta_1-\theta_2)$ occurs twice (neglecting self-absorption). But the star obstructs a portion of the ring, and this causes a sudden break in the contour (Fig. 1). Furthermore, in reality the velocities of the atoms depend upon the distance from the center of the star, and this will tend to make the curve somewhat smoother. As ρ is approximately proportional to λ, the resulting curve is identical with the contour. Since the contour is materially affected by the thickness of the ring, its extent in latitude and in distance, and by the size of the star, a considerable variety of curves may be constructed. But all of them share the property that the outer edges of the emission lines measure the components in the line of sight of the rotational velocity of the ring.

If the inclination is 0°, the ring shows no velocity displacements, and we observe a narrow, bright line. The fact that a perfectly narrow single emission line has not as yet been observed is quite in agreement with expectations, since the probability is very small that the inclination would be very close to 0. As a matter of fact, only one out of the thirty-four stars of Table III would be expected to have $75^\circ \leq i \leq 90^\circ$. If the equatorial velocity necessary for the formation of the nebulous ring is about 250 km/sec., the observed component of rotation for this one star would be of the order of 35 km/sec.

But if excessive angular momentum is relieved by the equatorial ejection of matter, it is not probable that fission could also occur. Why should some stars go into fission while others eject matter equatorially? There is doubtless an intimate relationship between close spectroscopic binaries and rapidly rotating single stars (α Virginis and η Urs. Maj.).[1] A solution may perhaps be found in the following ideas suggested by W. D. MacMillan.[2] Suppose that a binary star grows in mass and that the distance between the components diminishes. Such a growth might perhaps result from the gradual accumulation in the star of diffuse matter in interstellar space.[3] Recent computations by Markowitz (unpublished) show that if two components of a double star were joined together, the resulting body would in many cases be unstable. A star with extremely rapid rotation would result, and the excess of momentum would be relieved by the formation of a nebulous ring. According to MacMillan, the smaller of the two stars would be distributed in a ring around the larger and would result in a short time in a very oblate or lens-shaped star, in very rapid rotation. This hypothesis virtually reverses the direction of the phenomena usually attributed to fission. Unfortunately there seems at present to be no way to establish this direction by observation.

In conclusion it may be pointed out that our explanation of the origin of bright lines in the spectra of B-type stars is in good agreement with the observational results summarized in Section I of this

[1] *Astrophysical Journal*, **72**, 1, 1930.

[2] I am indebted to Professor MacMillan for helpful discussions of this problem.

[3] W. D. MacMillan, *American Mathematical Monthly*, **26**, 326, 1919.

paper. If the width of an emission line is due to Doppler effect, it should be proportional to the wave-length

$$\Delta\lambda = \lambda \frac{v \cdot \sin i}{C} = \text{const } \lambda \, .$$

The empirical equation found by Curtiss has the form

$$\Delta\lambda = C_1 \cdot \lambda + C_2 \, .$$

The proportionality with wave-length is actually present. The second constant in the formula of Curtiss means merely that at λ 3270 all stars would have the same line width, approximately 2.6 A. But in nearly all stars Curtiss measured only as far toward the violet as $H\delta$ and in only one star as far as $H\nu$. The formula therefore represents an extrapolation. It is probable that the limited resolving power of the spectrograph and perhaps also the weakening of the lines toward higher numbers of the series are responsible for the value of C_2 which, theoretically, would have been 0.

The fact that the emission lines vary in intensity is perhaps an indication that the emitting body is not a very stable one. If the orbits of the individual atoms in the ring are elliptical instead of circular, the intensities of the two components would not necessarily be the same. Nor would the components be spaced symmetrically on both sides of the normal wave-length. It is conceivable that rotation of the line of apsides of the elliptical orbits might cause a periodic variation in the relative intensities of the two bright components.

The distribution of intensities along the Balmer series has not yet been accurately investigated by the application of modern spectro-photometric methods. But qualitatively, at least, the rapid decline in intensity from bright $H\alpha$ toward the higher members of the Balmer series agrees well with laboratory results and with theoretical considerations.

Yerkes Observatory
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STUDIES IN PECULIAR STELLAR SPECTRA

I. THE MANGANESE LINES IN α ANDROMEDAE

By W. W. MORGAN

ABSTRACT

The strong lines of *ionized manganese* which in the past have been observed only in the spectrum of α Andromedae have been found in *thirteen other stars* of spectral classes B5–A0. It is fairly certain that the *stage of ionization is the second* (*Mn* III). In the light of the present observations the *behavior of ionized manganese* in stellar spectra seems to be *entirely normal.*

1. The predictions of the general theory of ionization, developed by M. N. Saha, R. H. Fowler, E. A. Milne, and others, are usually so closely in accordance with observation in stellar spectra that it is of some importance to determine whether the few apparently anomalous cases reported by various observers are real. As it now seems fairly certain that the stars in general have about the same relative abundance of the different elements, those stars which do not fit into the two-dimensional scale of temperature and pressure are of especial interest. Among the early A stars there are several groups which have seemed at one time or another not to be in accordance with the ionization theory. These are: (1) the *c*-stars, or supergiants; (2) stars in which the *Si* II doublet 4128 and 4131 is strong; (3) stars in which the ultimate *Sr* II lines 4077 and 4215 are of considerable intensity; (4) 12 α^2 Canum Venaticorum; (5) stars which resemble 37 θ Aurigae; (6) 21 α Andromedae. All representatives of the foregoing groups which have been classified in the *Henry Draper Catalogue* are designated as peculiar.

A few supergiant stars in the range A0–A5 which have very narrow, deep lines were formerly supposed to be in a small class by themselves. It is now thought, however, that their spectra fit in the ordinary scale of temperature. The increased intensity of the lines can be accounted for on the basis of thermal ionization.

The great strength of the *Si* II doublet 4128 and 4131 was formerly considered to be anomalous. It now seems that singly ionized silicon reaches a normal maximum at A0 and that the intensities of its lines are normal. The problem has, however, not as yet been fully investigated.

There are a few A-type stars in which the *Sr* II lines 4077 and 4215 are very strong. As these lines normally reach their maximum at about K5, they should be weak, if present at all, in A stars. The lines are very sensitive to changes in absolute magnitude as they become much stronger on passing from dwarfs to giants. This effect of absolute magnitude will possibly explain the apparently abnormal intensities in some A stars.

The spectrum of 12 α^2 Canum Venaticorum was found in 1900 by Sir Norman Lockyer and F. E. Baxandall[1] to contain a large number of strange, unidentified lines. Many of these lines were later identified by Baxandall[2] as being due to the rare earth europium. C. C. Kiess[3] later provisionally identified a number of the other lines as being due to terbium. The spectrum of 12 α^2 Canum Venaticorum has also been studied by H. Ludendorff,[4] A. Belopolsky,[5] Miss C. Anger,[6] and by A. Markov.[7] The spectrum of 36 τ^9 Eridani was described by O. Struve and C. Hujer[8] as being similar to that of α^2 Canum Venaticorum.

Lockyer and Baxandall[9] also announced in the spectrum of 37 θ Aurigae the presence of a number of well-marked lines which they were unable to identify. The *Henry Draper Catalogue* lists a few other stars as having spectra similar to that of 37 θ Aurigae. The spectrum of 37 θ Aurigae is given by the same authority as Aop.

Lockyer and Baxandall[10] gave the positions of a number of strange lines in the spectrum of α Andromedae. In a later paper Baxandall[11] identified most of these lines with those in the spark spectrum of manganese. This star has heretofore been considered abnormal and as almost unique in the intensity of the manganese lines.

[1] *Proceedings of the Royal Society of London*, A, **77**, 550, 1906.

[2] *Monthly Notices*, **74**, 32, 1913.

[3] *Publications of the Observatory, University of Michigan*, **3**, 106, 1923.

[4] *Astronomische Nachrichten*, **173**, 1, 1926.

[5] *Bulletin de l'Academie Impériale des Sciences de St. Pétersbourg* (series vi), **7**, 689, 1913; also *Astronomische Nachrichten*, **196**, 1, 1913, and *ibid.*, **234**, 93, 1928.

[6] *Astrophysical Journal*, **70**, 114, 1929.

[7] *Ibid.*, **72**, 301, 1930.

[8] *Ibid.*, **65**, 300, 1927.

[9] *Proceedings of the Royal Society of London*, A, **77**, 550, 1906.

[10] *Ibid.* [11] *Monthly Notices*, **74**, 250, 1914.

The stars 12 α^2 Canum Venaticorum, 37 θ Aurigae, and 21 α Andromedae are thus three of the most striking misfits in the thermal ionization sequence. The present paper is concerned with the study of the ionized manganese lines which were first found in α Andromedae. It was my purpose to ascertain whether or not the presence of these lines is really "abnormal" from the point of view of the modern theory of ionization.

2. The original discovery, by Lockyer and Baxandall, of a number of strong, unidentified lines in the spectrum of α Andromedae was made in 1906. The plates taken by them at South Kensington seemed to show slight changes in the relative intensity, position, and definition of some of the lines. In Lockyer's system of spectral classification, α Andromedae was placed in the "Markabian" group for which 54 α Pegasi is the standard star, located midway between Sirius (A0) and Algol (B8). Because of the strength of the helium lines, α Andromedae was placed closer to Algol in temperature than to Sirius. The most prominent of the strange lines were at $\lambda\lambda$ 3943.8, 3984.0, 4136.9, 4206.3, and 4282.4 IA. In 1913 Baxandall identified these lines, with the exception of 3984.0, with enhanced lines in the spectrum of manganese. Many other fainter lines were also found to be due to the same source. Attention was called to the fact that the relative intensities of the lines are not the same as in the laboratory. The line showing the greatest inconsistency was at 4344.04, which is of intensity 8 in the laboratory. In α Andromedae the lines 3943.78, 4137.01, 4206.41, and 4325.67 are all much stronger than 4344.04. The explanation given is that the difference in relative intensity is probably due to different conditions in the star from those in the laboratory. It does not seem necessary, however, to use this explanation, because the line 4344.04 occurs in the wing of $H\gamma$ at 4340 and for this reason is certainly greatly weakened.[1] A list was given of six lines in the spectrum of 50 α Cygni and of six lines in 9 α Canis Majoris which were possibly due wholly or in part to "protomanganese."

[1] The weakening of lines in the wings of the very broad hydrogen lines is due to the increased opacity of the stellar material due to absorption by hydrogen. In a wavelength in the wing of a Balmer line we do not see as deeply into the reversing layer as we do in the continuous spectrum (see Unsöld, Struve, and Elvey, *Zeitschrift für Astrophysik*, **1**, 314, 1930).

The spectrum of α Andromedae is given as A0p in the *Henry Draper Catalogue* with the remarks, "The spectrum is very peculiar. It resembles Class A0 in respect to the hydrogen and calcium lines, while lines 4026.2, 4267.4, and 4471.5 are of the same intensity as in Class B8. Several strong solar lines are present." The *Henry Draper Catalogue* contains one other bright star, 5 μ Leporis, which is noted as being similar to α Andromedae, but no further details are given.

The Mount Wilson revision of Rowland's *Preliminary Table of Solar Wave-Lengths* records a number of lines as being due to *Mn* II. One multiplet of singly ionized manganese has been picked out by M. J. Catalan in the far ultra-violet. This multiplet is well marked in the sun. Almost all of the other suggested identifications with *Mn* II are marked as questionable. T. Dunham, Jr.,[1] has listed a few lines in the spectrum of 33 α Persei as being possibly partly due to *Mn* II. Miss E. T. R. Williams[2] states that ionized manganese may be present in the spectrum of 9 α Delphini.

If the hydrogen lines and the H and K lines of ionized calcium be excluded from consideration, the spectrum of 21 α Andromedae resembles closely the spectrum of a normal B8 star except for the presence of the manganese lines and of a few other unidentified lines. The helium lines 4026 and 4472 are well marked; *He* 4144 and 4387 are easily visible, and, on the best Yerkes plates, 4121 is certainly present, although extremely faint. The singly ionized carbon line 4267 is equal in intensity to *Fe* II 4233. The *Si* II doublet 4128 and 4131 is fairly strong. Several of the strongest lines of *Fe* II are present. Between the limits 4000 and 4650 are the following *Fe* II lines: 4178, 4233, 4303, 4351, 4416, 4508, 4515, 4549, 4555, 4583, and 4629. Most of these lines are near the limit of visibility. Except for *Mg* II, 4481, the other singly ionized metals seem to have almost entirely disappeared. With the exception of the helium lines and carbon 4267, the high-temperature lines of type B do not appear. All of the lines in the spectrum are slightly diffuse, probably as a result of rotation of the star. The spectrum is, however, of fair quality.

Because of the general faintness of the metallic lines and the strength of helium, it seemed probable that the most promising place

[1] *Contributions from the Princeton Observatory*, No. 9, 1929.

[2] *Harvard Circular*, No. 348.

to search for other stars containing manganese lines would be in the range of classes B5–A0. During the last thirty years spectra of practically all B and A stars brighter than magnitude 5.5 and north of about $-25°$ declination have been obtained with the Bruce spectrograph attached to the 40-inch telescope of the Yerkes Observatory. A search was made through all of the stars of which measurable plates have been obtained in the range B5–A0 inclusive. Only one-prism plates were used, as Yerkes three-prism spectra do not extend farther into the violet than about 4300, and almost all of the ionized manganese lines are to the violet of this limit. I have examined the spectra of 362 stars on an average of about five plates for each star. Besides 21 α Andromedae and 5 μ Leporis, 12 other stars

TABLE I

Spectrum (H.D.)	No. of Stars Examined	Manganese Stars	Per Cent *Mn* Stars
A0	197	4	2.0
B9	38	4	10.5
B8	69	4	5.8
B5	58	2	3.4

were found which definitely showed some or all of the lines of manganese. Table I gives the number of manganese stars found as compared to the total number examined in each spectral subdivision. The percentages listed in the last column are small, owing, no doubt, to the faintness of the manganese lines. Many of the stars examined have very broad and hazy lines, believed to be such on account of rapid axial rotation of the stars. Since rotation very materially reduces the central intensity of a narrow line, it is clear that such faint lines as these of manganese will not be visible in stars with rapid rotations. It is therefore more representative to exclude the stars with rapid rotations (character of lines "Few, poor" on the Yerkes classification; see *Publications of the Yerkes Observatory*, **7**, Part I, and *Astrophysical Journal*, **64**, 1, 1926). The results are shown in Table II.

Table III lists the fourteen stars which show the lines clearly in order of right ascension. The last column of the table gives the estimates of the number and quality of the lines in the spectrum of each

star. These estimates were made a number of years ago in connection with measures for radial velocity and were used as a criterion of the order of accuracy to be expected. The Yerkes plates of 9 α Delphini, although of good quality, do not seem to confirm the presence of ionized manganese as suspected by Miss Williams. The spectral

TABLE II

Spectrum (H.D.)	No. Stars Less "Few, poor"	Manganese Stars	Per Cent *Mn* Stars
A0	110	4	3.6
B9	22	4	18.2
B8	35	4	11.4
B5	35	2	5.7

TABLE III

Star	α 1900	δ 1900	Magnitude	Spectrum (H.D.)	Character
21 α Andromedae	0^h03^m	$+28°32'$	2.2	A0p	Ff
+59°146 Cassiopeiae	0 51	+59 50	5.5	B9	Fg
α Sculptoris	0 54	−29 54	4.4	B5	Ff
53 Tauri	4 14	+20 55	5.4	B8	Fg
5 μ Leporis	5 08	−16 19	3.3	A0p	Mf
112 β Tauri	5 20	+28 31	1.8	B8	Ff
37 θ Aurigae	5 53	+37 12	2.7	A0p	Ff
23 γ Canis Majoris	6 59	−15 29	4.1	B5	Fg
14 Hydrae	8 44	− 3 04	5.2	B9	Ff
76 κ Cancri	9 02	+11 04	5.1	B8	Mf
26 π Bootis	14 36	+16 51	4.9	A0	Fg
6 υ Herculis	16 00	+46 19	4.6	B9	Fg
11 φ Herculis	16 06	+45 12	4.2	B9p	Mg
+33°3154 Lyrae	18 33	+33 23	5.5	B8	Fg

ABBREVIATIONS: Mg = Many, good Mf = Many, fair
Fg = Few, good Ff = Few, fair

lines are extremely broad and diffuse, probably because of a high speed of rotation. Other stars not included in Table III are suspected more or less strongly of containing ionized manganese. In some cases the plates are not of sufficiently good quality to permit certainty, and in others the lines are so extremely faint that some doubt is felt as to their reality. If fine-grain plates were available for all the stars from B5 to A0, numerous others would almost certainly be included. Although the range in spectral type of the four-

teen stars is from B5 to A0, the actual range in effective excitation is very small. Twelve of the fourteen stars contain the helium lines 4026 and 4472, and in no case is 4472 as strong as *Mg* II 4481. As the equality of these two lines is one of the criteria for spectral type B8, it can be seen how closely the stars are grouped together as far as state of excitation is concerned. It is apparent from Table III that the percentage of manganese stars is greatest at B9. In fact, only two of the stars, 37 θ Aurigae and 53 Tauri, can really be classed as A0 if the evidence of the metallic lines and of the presence of helium is used. It is of some interest to note that apart from the rapidly rotating stars, the classification of the A0 stars into divisions of "many lines" and "few lines" is roughly a separation of stars of lower from those of higher temperature. As a rule, the stars which are classified "Mg" and "Mf" owe their increased number of lines to the appearance of a large number of metallic lines of lower temperature, both neutral and ionized. In the "Fg" and "Ff" stars, practically all of the neutral and weak enhanced lines of iron and titanium have disappeared. The A0 stars having few lines form therefore an intermediate class between the B8 and B9 stars and A0. The only A0 star found to contain manganese which was classified as having many lines is 5 μ Leporis, and the reason for its classification as "Mf" is not because the metallic lines are numerous, but because the manganese lines themselves are more conspicuous than in any other star observed. Several of the stars, such as 5 μ Leporis, 29 π Bootis, and 76 κ Cancri, are, as far as the relative intensities of the spectral lines are concerned, almost identical with α Andromedae.

3. All of the lines attributed to "proto-manganese" by Baxandall which could be seen on Yerkes plates were measured for wavelength. Two plates were measured of α Andromedae, two of μ Leporis, and one of φ Herculis. The two plates of μ Leporis cover different parts of the spectrum and only two of the lines are duplicated. Table IV gives the measures of Baxandall and my own measures. The columns are: the laboratory wave-lengths determined by Lockyer; Lockyer's laboratory intensities in the arc and spark; wave-lengths in α Andromedae (Baxandall); wave-lengths in α Andromedae, μ Leporis, and φ Herculis (Morgan); the mean wavelengths (Morgan). There are three manganese lines observed in

21 α Andromedae by Baxandall which I did not measure. Two of these are outside the region of best definition on Yerkes plates. The lines at 4200, 4248, and 4282 were not observed by Exner and Haschek in the laboratory, but are all certainly present in α Andromedae. The line at 4300 is given as of intensity 2 in both arc and spark, while in Lockyer's list it is given as of intensity 2 in the spark and absent in the arc. There may thus be some doubt as to

TABLE IV

Lab.	Int. Laboratory		α And. (Bax.)	Int.	α And.	Int.	μ Lep.	Int.	φ Her.	Int.	Mean
	Spark	Arc									
3943.78....	2	0	3943.71	4	3943.74	4	3943.92	3-4	3943.91	1	3943.86
4000.05....	2	0	4000.00	1-2	3999.93	1-2	....	.....	....	.....	3999.93
4104.90....	3	0	4105.34	?2	4105.14	4	4105.03	3-4	....	.....	4105.11
4128.21....	2-3	.....	4128.11	4-5	4128.16	5-6	4128.07	7	4128.01	7	4128.12
4137.01....	3-4	0	4136.90	3-4	4136.88	4-5	4136.89	5	4137.02	5	4136.92
4200.25....	2	0	4200.70	1-2	4200.35	2	4200.40	3	....	.....	4200.37
4206.41....	4	0	4206.46	3-4	4206.14	5	4206.39	5	4206.00	2	4206.17
4242.30....	4	0	4242.35	2	4242.46	1-2	4242.50	3-4	....	.....	4242.45
4244.28....	1-2	0	4244.61	1	4244.42	1-2	....	.....	....	.....	4244.42
4247.95....	1	0	4247.72	2	4248.03	1-2	....	.....	....	.....	4248.03
4251.71....	5	0	....	.....	....	.....	4251.43	3-4	....	.....	4251.43
4252.98....	5	0	4253.28	2	4253.10	3	4252.97	4	4252.79	3	4252.99
4259.20....	4	0	4258.87	2-3	4259.29	3	4259.09	4-5	....	.....	4259.19
4282.50....	3	1-2	4282.72	2-3	4282.27	3-4	4282.35	4	4282.37	3-4	4282.31
4283.81....	1	0	4283.89	2	(4284.30)	2	(4284.32)	3	(4284.17)	3-4	(4284.26)
4292.20....	2-3	0	4292.11	2-3	4292.23	2	4292.33	3	4292.23	1-2	4292.25
4300.22....	2	0	4300.49	1-2	4300.20	1-2	4300.12	3	4300.18	4	4300.18
4326.67....	5	0	4326.64	3	4326.56	3	4326.75	4	4326.64	4-5	4326.62
4344.04....	8	0	4343.95	2	4344.04	2-3	4343.87	4	....	.....	4343.99
4348.47....	2	0	4348.35	2	4348.69	1-2	4348.55	1-2	....	.....	4348.62
4365.35....	1-2	0	4365.14	1	....	.....	....	.....	....	.....	....
4478.71....	2-3	0	4478.49	1-2	4478.46	1-2	4478.49	1-2	4478.56	1	4478.49
4755.74....	2	<1	4755.64	4	....	.....	....	.....	....	.....	....
4764.75....	2	0	4764.47	2	....	.....	....	.....	....	.....	....

whether it is actually enhanced in the spark. It may be that the line observed in α Andromedae is due entirely to *Ti* II, which has a strong line at 4300. Several other manganese lines coincide in position with enhanced metallic lines. There are *Cr* II lines at 4242.37, 4252.65, and 4284.20; 4343.99 may be blended with *Ti* II 4344.29. The strong *Si* II 4128.05 makes it impossible to express an opinion on the manganese line in the same position. There is an exceedingly faint line at 4136.9 in Sirius which is almost certainly due to neutral iron, but it seems impossible that this weak line could contribute sensibly to the well-marked manganese line in the same position in the hotter stars. The most distinctive of the unblended manganese lines are those at 3942.86, 4136.92, 4206.17, and 4326.62.

4. Lockyer and Baxandall[1] measured twenty-four enhanced lines in the spark spectrum of manganese. Only two of these lines are present in the arc spectrum. The list of Exner and Haschek includes a great many more lines, many of which are much stronger in the spark than any of the lines measured by Lockyer and Baxandall. It seems, therefore, that the conditions of excitation were decidedly higher in the apparatus used by the latter.

The multiplet relationships and successive stages of ionization of manganese are not known above the first stage, except for a single multiplet of *Mn* II in the far ultra-violet which was picked out by

TABLE V

Mn II MULTIPLET

Fuchs	Int. Arc	Int. Spark	Sun	I_R	α Cygni	I_W	E.P.
3441.999..........	2	30	3441.983	6	3442.07	3+	1.768
3460.332..........	2	20	3460.327	4d?	3460.33	3−	1.802
3474.050⎫.........	1	15	....	....	....	....	....
3474.139⎭.........			3474.151	2	3474.14	3	1.825
3482.918..........	2	12	3482.910	5d?	3482.93	3	1.825
3488.618..........	2	10	3488.679	4	3488.67	3	1.840
3495.840..........	1	7	3495.836	2	3495.78	2+	1.847
3496.815..........	1	3	3496.814	3	....	....	1.825
3497.540..........	1	6	3497.530	3	3497.55	2−	1.840

Catalan.[2] The lines of the multiplet range in wave-length from λ 3442 to λ 3497 and are thus far out of the range of ordinary stellar spectrograms. The multiplet is strong in the sun, and there can be no doubt that seven strong lines in the ultra-violet spectrum of 50 *α* Cygni measured by W. H. Wright[3] and attributed by him to manganese form the same multiplet of *Mn* II that is present in the sun. These lines are all strong in the arc and much enhanced in the spark spectrum. Table V gives the data on this multiplet. The columns are: the laboratory wave-lengths as measured in the arc by H. Fuchs;[4] the intensities in arc and spark, as given by Exner and Haschek; the wave-lengths in the sun, from the *Mount Wilson Revi-*

[1] *Tables of Wave-Lengths of Enhanced Lines, Solar Physics Committee,* 1906.

[2] *Philosophical Transactions of the Royal Society of London,* A, **223**, 161, 1922.

[3] *Lick Observatory Bulletin,* No. 332, 100, 1921.

[4] *Zeitschrift für Wissenschaftliche Photographie,* **14**, 239 and 263, 1915.

sion; the intensities in the sun on Rowland's scale; the wave-lengths in α Cygni according to Wright (reduced to I.A.); Wright's intensities estimated on an arbitrary scale of 1–5; and the excitation potentials.

The ionization potential of *Fe* I is 7.83, of *Ti* I is 6.80, and of *Mn* I is 7.40 volts. The second ionization potentials of these elements are: 16.5 volts (*Fe* II), 13.60 volts (*Ti* II), and 15.70 volts (*Mn* II). From the strength of the multiplet in the sun and in α Cygni, and also from analogy to *Fe* II and *Ti* II, it would be expected that *Mn* II would have its maximum at F0–F8. Unfortunately, very few stars have had their spectra studied so far in the ultra-violet, and no maximum of *Mn* II can be determined. It seems almost impossible, however, that the manganese lines in α Andromedae can belong to the first stage of ionization. The maximum of the lines in α Andromedae is very sharp, and occurs at a temperature of about 12,500°. The *Ti* II lines have almost if not entirely disappeared, and only the strongest half-dozen lines of *Fe* II are still present. Since there can be no doubt that the lines are due to manganese in some stage of ionization, it seems almost certain that this stage is the second (*Mn* III). This conclusion is in accordance with the behavior of the lines in the laboratory. They are absent in the arc, and are still comparatively weak lines in the spark, unless the excitation is very high. The strength in most of the stars of the helium lines 4026 and 4472, and of the *C* II line, 4267, shows that the effective excitation must be decidedly higher than in the normal A0 star. If this interpretation is correct, it would follow that the third ionization potential of manganese, not so far determined from spectroscopic analysis, is rather low, hardly more than 20–25 volts. It would be of interest to determine this quantity spectroscopically.

5. In order to determine more accurately the similarities among the stars found to contain *Mn* III, the intensities of a number of characteristic lines were estimated on several good plates of each star. The number of plates on which the estimates were made averaged about three per star. There were at least two plates in every case. The estimates were made on an arbitrary scale of 1–10. A line of intensity 1 was doubtfully present, while the strongest lines in A stars with the exception of the hydrogen lines were classed as of

intensity 10. Plates of a few of the brighter stars had been recently obtained here on the fine-grain Eastman Process emulsion on which the faint lines appear appreciably stronger than on ordinary fast plates. The material was made homogeneous by applying a systematic correction to the estimates made on the Process plates. This correction was determined by comparing estimates made on process and rapid plates of α Andromedae. The lines whose intensities were estimated were: (1) the strongest *Mn* III lines in α Andromedae; (2) the *He* I lines 4026 and 4472; (3) the *Si* II lines 4128 and

TABLE VI

Mn III STARS IN ORDER OF RATIO $\frac{4481}{4472}$

Star	H.D.	$\frac{4481}{4472}$	4026	4077	4128	4130	4137	4206	4215	4233	4267
53 Tau	B8	.....	.....	.....	6.0	4.7	4.3	5.3	.....	3.0	.....
θ Aur	A0	.....	.....	2	7.8	7.8	1.8	3.0	2.5	6.0	.....
υ Her	B9	7.8	2.3	3.3	5.7	5.3	2	4.3	3.0	3.7	.....
59°146	B9	5.0	1.3	.....	3.7	4.3	2.6	3.3	.....	2.0	1.0
μ Lep	A0	4.3	3.3	3.7	7.0	7.0	4.8	4.8	3.7	5.0	4.0
14 Hya	B9	3.8	3.5	1:	6.0	5.5	5.0	4.0	1:	1.5	.....
π Boo	A0	3.5	3.7	4.0	6.7	6.0	6.0	5.0	3.3	4.0	3.3
φ Her	B9	2.8	3.5	1	6.8	6.3	5.0	2.0	2.0	6.3	1:
α And	A0	2.5	4.0	.....	5.6	4.8	4.3	5.0	.....	3.0	3.6
κ Cnc	B8	2.1	3.7	.....	6.7	6.0	5.0	4.0	2	4.0	3.3
γ CMa	B5	1.7	5.5	.....	5.5	5.0	3.0	3.5	1:	3.5	1.5
33°3154	B8	1.5	3.3	.....	5.3	5.3	5.3	4.0	1:	1.0	.....
β Tau	B8	1.5	5.0	.....	4.8	4.8	1.8	1.4	.....	3.2	3.8
α Scl	B5	1.1	4.0	.....	4.0	4.0	2.5	.....	.....	1:	5.5

4131; (4) the *Sr* II lines 4077 and 4215; (5) the lines *Fe* II 4233, C II 4267, and *Mg* II 4481. The ratio of the intensities of *Mg* II 4481/*He* I 4472 was used to arrange the stars in order of effective excitation. The first two stars, θ Aurigae and 53 Tauri, do not show the helium lines, but they would be classed as A0 on the basis of the intensities of the metallic lines. Table VI gives the estimated intensities. The columns are: the name of the star; the H.D. spectral classification; the ratio 4481/4472; and the estimated intensities of the characteristic spectral lines.

The *Henry Draper Catalogue* classes 53 Tauri as B8, although the helium lines seem to be absent. It is probable that the hydrogen lines and K were used in the classification. The star was announced as a spectroscopic binary by the Lick Observatory and spectral type

revised to A5. The spectrum is rather peculiar in that the strongest lines of *Ti* II are as strong or stronger than *Fe* II. Because of the great strength of *Mg* II 4481 it does not seem possible to classify the spectrum later than A0.

The *Henry Draper Catalogue* classifies θ Aurigae as peculiar, with the following remarks: "The lines 4128.1 and 4131.1 are very strong. The line K is very faint." The spectrum is more completely described in *Harvard Annals*, **28**: "This star closely resembles 12 Canum Venaticorum. . . . . It differs from that star only in the altered intensity of several faint lines, and the presence of several others not seen in 12 Canum Venaticorum." Although the lines which make the spectrum distinctive are not the same as those in α Andromedae, the stronger *Mn* III lines are certainly present.

The star 59°146 Cassiopeiae is β 1099. The component stars are $6^{m}.1$ and $6^{m}.8$ and are separated by a distance of $0''.2$. They are in rapid angular motion. This probably explains why all of the lines are systematically fainter than in the other stars.

Harvard Annals, **28**, describes μ Leporis as follows: "This star resembles 21 α Andromedae, so far as can be ascertained from plates taken with two prisms." The *Mn* III lines are more strongly marked in this star than in any of the others. In spite of the fact that the quality of the lines was estimated as "Many, fair" by the Yerkes observers, they are extremely narrow and deep. The *Sr* II lines, 4077 and 4215, are well marked.

The star 26 π Bootis is Σ 1864. The magnitudes of the components are 4.9 and 6.0, and their distance is $5''.8$. There is a very slow progressive change in position angle. The brighter star is the one which contains the *Mn* III lines. The *Sr* II lines are also well marked in this star.

The star φ Herculis is noted by Miss Williams[1] as having a spectrum similar to α Andromedae in the strength of the helium lines and of K. She states, however, that the manganese lines were not seen in this star. The stronger *Mn* III lines are clearly visible on all of the Yerkes plates of good quality. The spectral lines are similar to 5 μ Leporis in their narrowness and depth.

Miss Williams reclassifies the spectrum of α Andromedae as B8.6. Miss Payne[2] states that the enhanced lines of manganese are

[1] *Harvard Circular*, No. 348. [2] *Stellar Atmosphere*, p. 172.

broadly winged. All of the lines are slightly broadened, probably due to rotation, but the manganese lines do not seem to differ in appearance from the other lines of the same intensity in the spectrum. The star α Andromedae is a spectroscopic binary having a period of 96.7 days. Only one spectrum is visible.

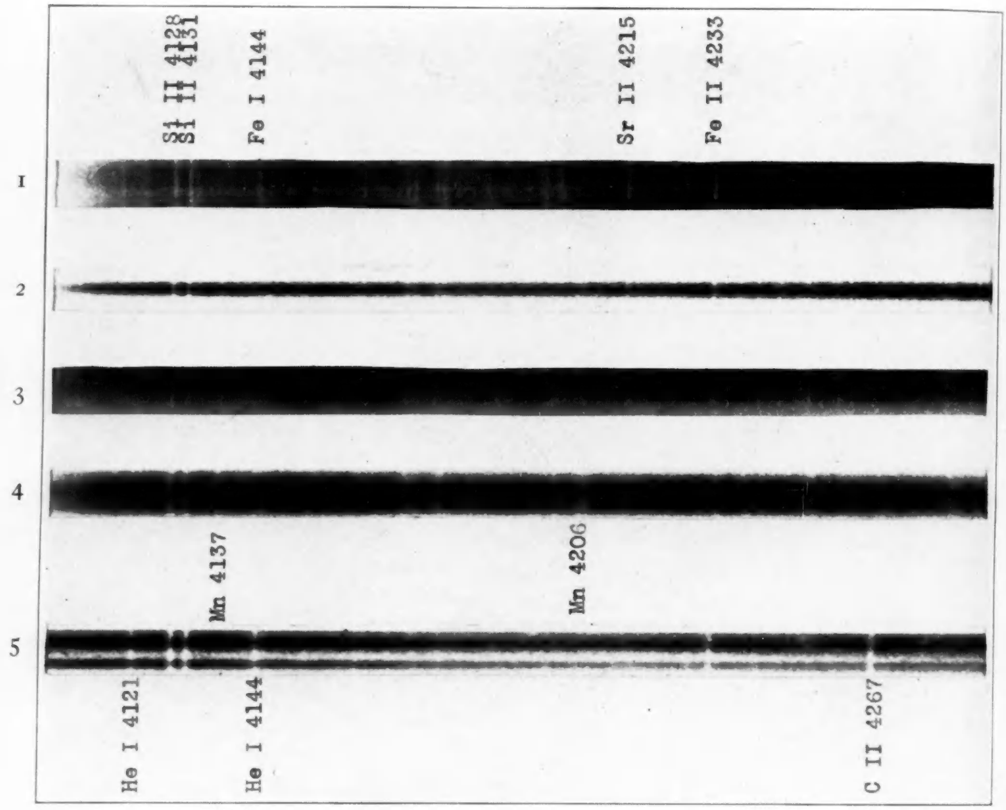
The variability in radial velocity of 76 κ Cancri was announced by Frost and Adams in 1904. The lines were reported to be double. All of the principal *Mn* III lines are well marked in this star, including the one situated at 4479, just to the violet of *Mg* II 4481. The line at 4479 was measured on several plates by Frost and Adams as the component of 4481 in the second spectrum. I have re-examined the plates on which the double lines were measured. There are no other clearly marked duplicities among the other lines, and there seems to be some doubt as to whether the spectra of both components are visible. The spectrographic orbit has been computed by H. Ichinohe using measures of the stronger component exclusively.

The star $+31^\circ 3154$ Lyrae is Σ 2349. As the magnitude of the fainter component is 10.7 and as the system is probably only an optical one, the companion can have no appreciable effect on the spectrum of the brighter star.

Although, as a rule, the *Mn* III lines are present when the *Si* II doublet 4128 and 4131 is strong and when the helium lines 4026 and 4472 are faint but certainly visible, there are a few stars fulfilling the foregoing conditions which do not seem to contain manganese. It is well known, however, that the stars cannot be arranged in a one-dimensional sequence, and when the general faintness of the *Mn* III lines is considered it seems safe to assume that the appearance of doubly ionized manganese in a normal star of class B9 having lines of good quality is a more or less common phenomenon.

The parallaxes of all the manganese stars, with the exception of α Sculptoris, are included in Schlesinger's recently published *Catalogue of Bright Stars*. The parallaxes have been taken from all sources, and, as the probable errors are not given, the order of accuracy of the deduced absolute magnitudes is somewhat uncertain. Table VII gives the name of the star, the visual magnitude, the parallax from Schlesinger's *Catalogue,* and the absolute magnitude computed from the parallax.

PLATE I



EXAMPLES OF STELLAR SPECTRA

(1) Sirius; (2) φ Herculis; (3) μ Leporis; (4) α Andromedae; (5) β Orionis. The spectra of φ Herculis, μ Leporis, and α Andromedae show the two strongest lines of ionized manganese. Sirius (A0) and β Orionis (B8), in which ionized manganese is absent, are shown to make clear the narrow limits within which the lines occur.

The mean absolute magnitude of the thirteen stars is +0.01. This is in almost exact agreement with the mean absolute magnitude of stars of spectral class A0, which is, according to Russell, $0^M_.0$. The manganese stars thus seem to be perfectly normal with respect to their absolute magnitudes.

It seems, therefore, safe to conclude (1) that the stage of ionization of the manganese lines in α Andromedae and in the thirteen other stars is the second (*Mn* III); (2) that the occurrence of manganese lines is a normal feature of many stellar spectra of types B8–A0; (3) that the maximum of *Mn* III at B9 is in fair agreement with the maxima of other elements having approximately the same ionization potential; (4) that the stars containing *Mn* III are not unusual with regard to their absolute magnitudes.

TABLE VII

ABSOLUTE MAGNITUDES

Star	m_v	Par.	M
α And	2.2	0″.040	+0.2
+59°146	5.5	8	.0
53 Tau	5.4	10	+ .4
μ Lep	3.3	30	− .7
β Tau	1.8	35	+ .5
θ Aur	2.7	32	+ .2
γ CMa	4.1	12	− .5
14 Hya	5.2	9	.0
κ Cnc	5.1	8	− .4
π Boo	4.9	16	+ .9
υ Her	4.6	11	− .2
φ Her	4.2	15	+ .1
+33°3154	5.6	7	−0.3

Plate I shows spectra of three of the manganese stars, with Sirius and Rigel added for comparison.

I wish to express my thanks to Professor Struve for suggesting the problem and for advice and suggestions while the work was in progress. I wish also to thank Professor Frost for the use of the great collection of Yerkes spectrograms and for the opportunity of obtaining additional plates with the 40-inch telescope.

WILLIAMS BAY, WIS.
December 5, 1930

THE TITANIUM COMPARISON SPECTRUM AS A PHOTOMETRIC SCALE

By PHILIP C. KEENAN

ABSTRACT

In order to provide photometric calibration for early stellar spectrograms lacking sensitometer exposures the *relative intensities of eighteen lines in the Ti comparison spectrum were determined.* Measurements of *total absorption of stellar hydrogen lines* by means of this scale *agree within 15 per cent* with those obtained by the use of the ordinary sensitometer curves.

The practice of impressing a photometric scale on stellar spectrograms was adopted at the Yerkes Observatory in July, 1928. The earlier plates, approximately ten thousand in number, lack such a scale, but it is highly desirable that photometric measurements be extended to them, especially since among the stars represented are many with variable hydrogen lines, and also several novae. Therefore, it was suggested by Messrs. Struve and Elvey that a method of calibration by means of the relative intensities of lines in the comparison spectrum be developed. A similar scale has been worked out at Harvard by F. S. Hogg,[1] who made use of the theoretical formulae to compute the intensities within selected iron multiplets, and applied the resulting curve to several slit spectrograms taken at the Dominion Astrophysical Observatory.

It was decided that it would be most feasible to obtain the relative intensities of the comparison lines on our plates empirically by measuring their densities on the newer spectrograms provided with sensitometer exposures. The sensitometer, which was constructed in our shop and was similar to one previously designed and used here by Professor Ross, has fourteen circular openings of different known areas, illuminated from below by an ordinary electric lamp behind a diffusing screen of opal glass. The exposures are arranged in two rows parallel to the stellar and comparison spectra, as may be seen in Figure 1, a reproduction of two typical plates.

The spark apparatus used to produce the comparison spectrum on all spectrograms taken since 1900 has been described by E. B. Frost

[1] *Harvard Circular*, No. 337, 1929.

and W. S. Adams.[1] It is provided with an induction coil to suppress the air lines, and has a rotating drum permitting the rapid substitution of different pairs of electrodes. Titanium has been employed

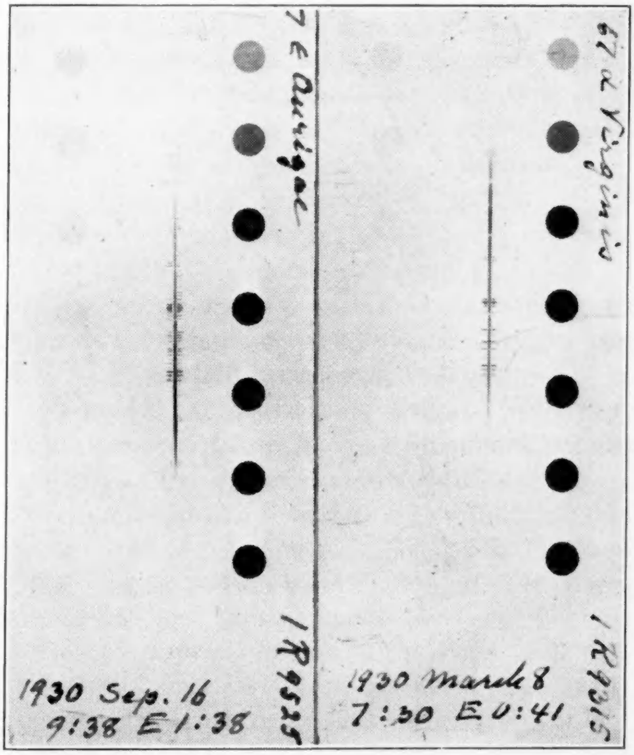


FIG. 1.—Typical one-prism stellar spectrograms. The difference in contrast between the Eastman 40 emulsion (Plate 1R 9525) and the Eastman Process emulsion (Plate 1R 9315) is conspicuous.

for all the plates, with the occasional addition of iron, or other elements.

The titanium spark spectrum has, unfortunately, no single multiplet in the photographic region covering the required range of density, and consequently it was necessary to make use of several multiplets. Lines from as many multiplets as possible were taken in order to minimize systematic errors, selection of individual lines

[1] *Publications of the Yerkes Observatory*, **2**, 6, 1903.

being based on freedom from blends and suitability of density. All measurements of density were made with the registering thermoelectric microphotometer designed by Mr. Elvey and used for the determinations of line contours here. In the operation of the microphotometer there is danger of a vertical shift of the light-beam on the thermopile when the star spectrum is placed in position for measurement instead of the comparison lines, or vice versa, since it is necessary to slide the plate-carrier out of the machine to make the change. This source of error may be in great part obviated through care in adjusting the position of the image on the second and defining slit by means of the cross-wires in the viewing telescope.

As arranged for this work, with a magnification of 30 on single-prism spectrograms, the speed of recording is approximately 8 A per minute in the photographic region, so that it was desirable to restrict the range of wave-lengths in order to hold the time of measurement to a convenient length. After a number of preliminary tests, eighteen titanium lines distributed between λ 4338 and λ 4572 were chosen and the intensities from twenty-two microphotometer curves averaged.

The plates measured were well distributed over the time interval from July 22, 1928, to May 9, 1930, and included some taken in winter as well as those of the summer months, since it was suspected at first that the spark might be sufficiently influenced by the extremes of the temperature experienced here, ranging from $-18°$ C to $+30°$ C during the time considered, to change the relative intensities of the lines, though the complete data later showed no evidence of such an effect.

The data are presented in Table I. The designations of multiplets in the first column and the estimated intensities by A. S. King in the third are from H. N. Russell.[1] Wave-lengths are given in the second column, followed by the measured relative magnitudes in the fourth.

The agreement between King's intensities in the spark and those measured here is fair, though considerable variation even within multiplets is apparent. The estimated values are too rough to bring out any systematic differences due to changes with wave-length of

[1] *Astrophysical Journal*, **66**, 283 and 347, 1927.

the absorption-curve of the lens and prism system of the spectrograph, but such are known to be appreciable and constitute a definite objection to the use of theoretical intensities, which would not be applicable unless the instrumental absorption-curve were accurately determined. This source of error does not affect the validity of the experimental scale, since the same set of lines is to be used for every single-prism plate. For the spectrograms taken with two or three prisms it would be practically necessary to calibrate a new group of

TABLE I

RELATIVE INTENSITIES OF *Ti* COMPARISON LINES

Multiplet	Line	Estimated Spark Intensity (King)	Relative Magnitude
34 *Ti* II	4338 A	50	0.41
34 II	4344	2	2.39
33 II	4351	1	2.95
32 II	4367	15	1.48
29 II	4399	35	1.04
190 I	4423	10	2.19
24 II	4468	50	0.14
181 I	4471	20	1.92
181 I	4481	30	1.43
181 I	4496	20	2.13
24 II	4501	40	0.21
172 I	4512	40	1.32
172 I	4518	50	1.01
172 I	4523	40	1.11
172 I	4527	35	1.36
172 I	4552	35	1.13
172 I	4555	30	1.34
22 II	4572	50*r*	0.00

lines covering a shorter range of wave-lengths and including additional lines made available by the increased dispersion.

In order to test the accuracy of the scale, the contours of $H\gamma$ in 85 η Ursae Majoris on two recent plates, 1R 9314 (Eastman process) and 1R 9362 (Eastman 40), as determined by the ordinary sensitometer scale and by the titanium spectrum, were plotted in Figure 2. In both cases the total absorption given by the new method is somewhat below that obtained by the normal procedure. However, that does not necessarily indicate the presence of systematic errors in the scale, for other trial plates have given deviations in the opposite direction.

The effect of changed conditions of excitation in the spark on the relative intensities of lines in different multiplets is well illustrated

in the calibration-curves for 1R 9314, where the six points corresponding to lines in multiplet 172 of *Ti* II are specifically indicated

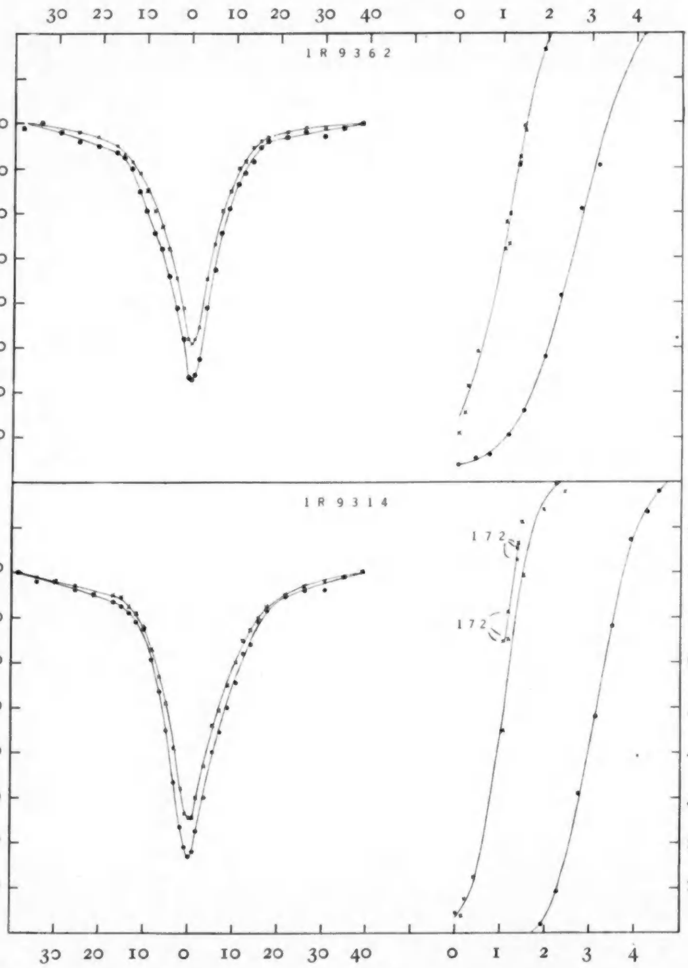


FIG. 2.—85 η Ursae Majoris. Contours of $H\gamma$ are on the left. Ordinates represent percentage absorption and abscissas wave-length in angstroms from the center of the line. Calibration curves are on the right, with deflections in millimeters as ordinates and relative intensities in magnitudes as abscissas. Sensitometer curves and the corresponding contours are indicated by circles, titanium calibration curves and contours by crosses.

and show a definite shift to the left of the curve given by the remaining lines, both normal and enhanced. This is the largest shift

of the sort observed on any of the test-curves thus far plotted, and in most cases the points corresponding to individual lines within a given multiplet are scattered about the mean calibration-curve given by all the lines. This may be seen from Table II, in which a plus sign indicates that the intensity given by the line falls below that of the mean curve for the same galvanometer deflection, while

TABLE II

SIGN OF RESIDUALS FROM MEAN CALIBRATION-CURVE FOR INDIVIDUAL LINES

Line	Multiplet	Plate 1R							
		9080	9153	9323	9318	9301	8978	9314	9362
4338	34	o	+	−	+	......	−	−	+
4344	34	o	−	−	−	−	−	−	o
4351	33	o	−	−	o	−	o	......	......
4367	32	+	+	o	−	−	−	−	−
4399	29	+	−	+	−	−	+	−	+
4423	190	+	+	o	−	+	+	+	+
4468	24	+	+	+	o	+	+	−	−
4471	181	+	−	o	−	−	o	−	o
4481	181	−	o	o	+	−	+	+	+
4496	181	−	o	o	+	+	+	......	o
4501	24	+	+	+	−	+	+	o	+
4512	172	+	−	+	+	o	o	+	o
4518	172	−	o	+	+	+	+	+	+
4523	172	−	o	o	+	+	o	+	−
4527	172	+	−	+	+	+	o	+	o
4552	172	o	o	−	o	o	−	+	+
4555	172	+	o	+	o	+	o	+	o
4572	22	−	−	−	−	−	o	o	−

a negative sign corresponds to a residual in the other direction. A zero means close agreement with the mean.

The table shows that the spark potential has been fairly stable over a period of several years. Upon this fact and the readiness with which systematic shifts can be detected when the curves are drawn rests the justification of the use of both arc and spark lines of the comparison spectrum of titanium in forming a scale for the calibration of a plate. However, the magnitude of the errors, 14 and $13\frac{1}{2}$ per cent in percentage absorption for the two contours shown, indicates the caution necessary in interpreting photometric data obtained by its use.

YERKES OBSERVATORY
November 22, 1930

NOTICE TO CONTRIBUTORS

There is occasionally published in the *Astrophysical Journal* a Standing Notice (for instance, on pages 179-180 of the number for September, 1917). This is principally intended to guide contributors regarding the manuscript, illustrations, and reprints. This notice contains the following paragraph:

> Where unusual expense is involved in the publication of an article, on account of length, tabular matter, or illustrations, arrangements are made whereby the expense is shared by the author or by the institution which he represents, according to a uniform system.

The present sheet has been printed for amplifying further that paragraph.

The "uniform system" according to which "arrangements are made" is as follows: The cost of composition in excess of $50, and of stock, presswork, and binding of pages in excess of 40 pages, for any one article shall be paid by the author or by the institution which he represents at the current rates of the University of Chicago Press. When four articles from one institution or author have appeared in any one volume, on which the cost of composition has amounted to $50 each, or when the total cost of composition incurred by the *Astrophysical Journal* on articles for one institution has reached the sum of $200, the entire cost of the composition, stock, presswork, and binding of any additional articles appearing in that volume shall be paid by the author or by the institution which he represents.

As to illustrations, the arrangements cannot be quite as specific, but it may be generally assumed that not more than three halftone inserts can be allowed without payment by the author. The cost of paper, presswork, and binding for each full-page insert is about $8.00, aside from the cost of the halftone itself. In the matter of zinc etchings, considerable latitude has to be allowed, as in many cases diagrams take the place of more expensive tables. It may be assumed, however, that it will seldom be possible for the *Journal* to bear an expense of over $25 for diagrams and text illustrations in any one article.

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Reprints of articles, with or without covers, will be supplied to authors at cost. No reprints can be furnished unless a request for them is received before the *Journal* goes to press.

Every article in the *Astrophysical Journal*, however short, is to be preceded by an abstract prepared by the author and submitted by him with the manuscript. The abstract is intended to serve as an aid to the reader by furnishing an index and brief summary or preliminary survey of the contents of the article; it should also be suitable for reprinting in an abstract journal so as to make a reabstracting of the article unnecessary. For details concerning the preparation of abstracts, see page 176 in the September, 1928, number of the *Journal*.

THE EDITORS